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Control of Information in Working Memory:

Encoding and Removal of Distractors in the Complex-Span Paradigm

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Abstract

The article reports four experiments with complex-span tasks in which encoding of memory items alternates with processing of distractors. The experiments test two assumptions of a computational model of complex span, SOB-CS: (1) Distractor processing impairs memory because distractors are encoded into working memory, thereby interfering with memoranda; and (2) free time following distractors is used to remove them from working memory by unbinding their representations from list context. Experiment 1 shows that distractors are erroneously chosen for recall more often than non-presented stimuli, demonstrating that distractors are encoded into memory. Distractor intrusions declined with longer free time, as predicted by distractor removal. Experiment 2 shows these effects even when distractors precede the memory list, ruling out an account based on selective rehearsal of memoranda during free time. Experiments 3 and 4 test the notion that distractors decay over time. Both experiments show that, contrary to the notion of distractor decay, the chance of a distractor intruding at test does not decline with increasing time since encoding of that distractor. Experiment 4 provides additional evidence against the prediction from distractor decay that distractor intrusions decline over an unfilled retention interval. Taken together, the results support SOB-CS and rule out alternative explanations.

Keywords: working memory, complex span, interference, decay

Control of Information in Working Memory:

Encoding and Removal of Distractors in the Complex-Span Paradigm

Working memory is a system for providing access to information for processing that can hold only a limited number of distinct representations at the same time (Baddeley, 2012; Cowan, 2005; Oberauer, 2009). The currently most popular experimental paradigm for studying working memory, and for measuring its capacity, is the complex-span task (Conway et al., 2005; Daneman & Carpenter, 1980). Complex-span tasks involve the interleaving of two competing tasks: Encoding elements of a list for immediate serial recall alternates with brief episodes of processing material that is typically unrelated to the memory list. For instance, participants could be asked to remember six consonants in their given order, and presentation of consonants alternates with arithmetic tasks (Turner & Engle, 1989), or with reading aloud a short series of words (Lewandowsky, Geiger, Morrell, & Oberauer, 2010). From here on, we will refer to the elements of the memory list as *memory items* or *memoranda*, and to the material to be dealt with in the interleaved processing episodes as *distractors*. The complex-span task is a popular tool for studying working memory because it combines several demands that theorists assume to tax working memory: Short-term maintenance combined with concurrent processing of unrelated material, and the need to minimize distraction by the processed material. Understanding how the cognitive system meets these demands is therefore an important milestone towards understanding the central role of working memory for cognition.

We recently developed a computational model of people's behavior in the complex span paradigm, the SOB-CS model (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). SOB-CS is an extension of the SOB model of serial recall (Farrell, 2006; Farrell &

Lewandowsky, 2002) to complex span.[1] SOB-CS is a two-layer connectionist network, with one layer for representing memory items and the other layer for representing their list positions (Figure 1A). The model uses distributed representations for both items and positions. A memory list is encoded by binding each item to the corresponding list position through rapid Hebbian learning. For instance, the list ABCD is encoded by binding A to Position 1, B to Position 2, and so on. At recall, the model steps through the positions in the required recall order, using them as retrieval cues for the items bound to them.

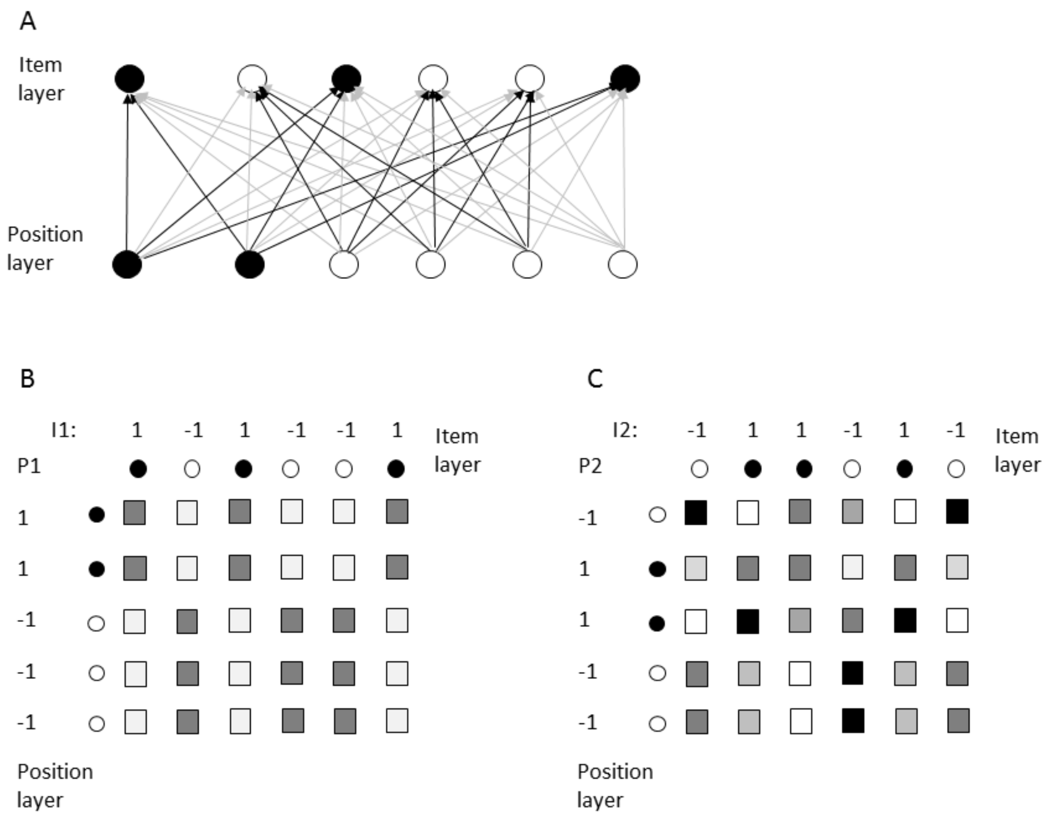


Figure 1: Schematic of SOB-CS. A: Two-layer neural network after acquiring the binding between one item and its position. Distributed representations are shown as patterns of activation across the units (shading of circles), and their bindings as patterns of connection

[1] SOB stands for “Serial Order in a Box”, and CS for “Complex Span”

weights (arrows). B: The same state of the network as in A, showing item and position representations as vectors and their binding as matrix of connection weights. C: The state of the network after encoding a second item by binding it to the second position. Superposition occurs in the binding matrix, which adds together the patterns of connection weight changes from each item-position binding.

In this model, the limited capacity of working memory arises from interference between distributed representations. There are two kinds of interference, interference by *confusion* and interference by *superposition* (Oberauer, Farrell, Jarrold, Pasiecznik, & Greaves, 2012). Interference by confusion means that the target item is confused with another element of the task vocabulary. The task vocabulary includes all potential recall candidates – for instance, when the task is to recall a list of consonants, then all consonants are elements of the vocabulary. Interference by confusion therefore can result in an order error (i.e., a transposition) when the target item is confused with another list item, or in an item error (i.e., recall of an extra-list item) when the target item is confused with an element of the vocabulary not in the current list.

In a complex-span task there is the possibility of confusing an item with a distractor, as long as the distractor is part of the vocabulary. For instance, in the classic reading-span task, in which participants read sentences and try to remember the last word of each sentence (Daneman & Carpenter, 1980), the non-final words of the sentences are distractors that arguably belong to the task vocabulary (i.e., words), and intrusions of such non-final words have been observed (Chiappe, Hasher, & Siegel, 2000; De Beni & Palladino, 2000; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998). In contrast, more recent versions of complex span use clearly different stimulus categories as memoranda and distractors – for instance, people read sentences and remember lists of letters. People hardly confuse letters with words at recall because words are not part of the vocabulary for letter recall. In SOB-CS, there is no interference by confusion between representations of clearly distinct classes, but there is still interference by superposition. Interference by superposition arises when multiple item-position bindings are encoded in the same matrix of connection weights between the item and the position layer (Figure 1B). Because both items and positions are coded by distributed representations, their binding is a pattern of changes across the entire weight matrix. The pattern of weight changes that stores each binding distorts all other bindings that are stored in the weight matrix at the same time (Figure 1C).

SOB-CS is based on two key assumptions that distinguish this model from other models of working memory: First, representations of the distractors, as well as other representations generated during the processing episodes, are obligatorily encoded into working memory (cf. Logan, 1988), thereby adding to the interference in the system. Specifically, distractor representations are associated to the position of the immediately preceding item, so that they interfere most with that item. To the degree that position representations overlap with neighboring positions, interference spreads to neighboring list items. Second, when there is free time following processing of a distractor, that time can be used to remove the distractor representation from working memory, thereby reducing the amount of interference with the memoranda. The first assumption explains why performance on complex-span tasks is worse than on simple-span tasks, which test immediate recall without an additional processing assignment. The second assumption explains why complex-span performance is better when the processing task is demanded at a slower pace (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007). In this article we provide evidence for both assumptions.

We used a version of the complex-span paradigm introduced by (Oberauer, Farrell, et al., 2012) that enabled us to gauge to what extent distractor representations entered working memory. In this version of the paradigm, the same kind of material – in the present experiments, concrete nouns – is used for both memory items and distractors, so that distractors become part of the task vocabulary. We tested memory by asking participants to select the memoranda from an array of words containing all the list items, all or a subset of the distractors, and a set of non-presented lures (i.e., words not presented in the current trial). To the extent that distractors are represented in working memory at the time of test, participants should tend to select them with a higher probability than non-presented lures. We will refer to people's tendency to erroneously select distractors for recall as *distractor intrusions*. We use distractor intrusions, a reflection of interference by confusion, to gauge the strength with which distractors are represented in working memory at the time of test. This strength is also an important determinant of interference by superposition, so that distractor intrusions can be used to indirectly measure the degree of interference by superposition. Because interference by superposition also arises between memory contents of different classes (e.g., between words and letters, and even to some extent between verbal and non-verbal materials), we can use distractor intrusions to test the assumptions of SOB-CS about interference between distractor processing and memory in general, not only for the specific case in which distractors and memoranda come from the same content class.

The logic of our approach is as follows: In Experiment 1 we varied the free time following each distractor. Distractors were selected for recall more often than non-presented lures, demonstrating that distractors are encoded into working memory. In addition, we show that the tendency to recall distractors diminished with longer free time, as predicted when free time is used for removing distractors from working memory. An alternative explanation for the effect of free time is that people use that time for strengthening their representations of the memoranda through some form of rehearsal or refreshing (Barrouillet et al., 2007). Because the memoranda are strengthened relative to the distractors, the latter intrude less frequently at test. To test this explanation, in Experiment 2 we asked people to process all distractors *before* presentation of the memory list. We found that longer free time following each distractor again reduced distractor intrusions and improved memory, even though that free time could not be used for rehearsing or refreshing of memory items that had yet to be presented. Another alternative explanation for the beneficial effect of free time is that distractor representations in working memory simply decay during that time, while representations of the memoranda are actively maintained to prevent them from decaying. If that were the case, people's tendency to select distractors for recall should decline over any variation of the time between their processing and the time of recall. We tested this prediction in Experiments 3 and 4, varying the time between distractor processing and test in two ways, and found that the prevalence of distractor intrusions did not diminish as a function of the mere passage of time. Because there is no reason to assume that people rehearse or refresh distractor representations, this finding rules out the possibility that distractor representations fade away through passive decay. We confirmed the accuracy of the predictions that we derived from SOB-CS by running simulations of all experiments. The simulation results are reported in Appendix A; the model code, written in Matlab, is available on the first authors' web page.[2] These simulations are meant to provide qualitative predictions, rather than a close quantitative approximation to the present data. Therefore, rather than fitting the model to the data by estimating optimal parameter values, we used SOB-CS with its standard parameter values, making only minimal adjustments for the specific characteristics of the present experiments. Because the focus of the present work is on testing qualitative predictions derived from core

[2] http://www.psychologie.uzh.ch/fachrichtungen/allgpsy/Software_en.html

assumptions of the model, we aimed to keep the article non-technical and moved all technical details into the Appendix.

Experiment 1

In our first experiment participants attempted to remember lists of five nouns. Each list word was followed by one distractor word (another noun). Participants made a judgment on each noun presented, regardless of whether it was a memory item or a distractor: They decided whether the object the noun refers to is larger or smaller than a soccer ball. Between trials we varied the free-time interval following each decision on a distractor; free time following memory words was held constant (at 0.2 s). The free-time intervals following distractors were chosen such that SOB-CS predicts little distractor removal for the short free time (0.2 s) and substantial removal for the long (1.5 s) free-time interval (for simulations see Oberauer, Lewandowsky, et al., 2012). The top two rows of Figure 2 show the time lines of trials in the two conditions.

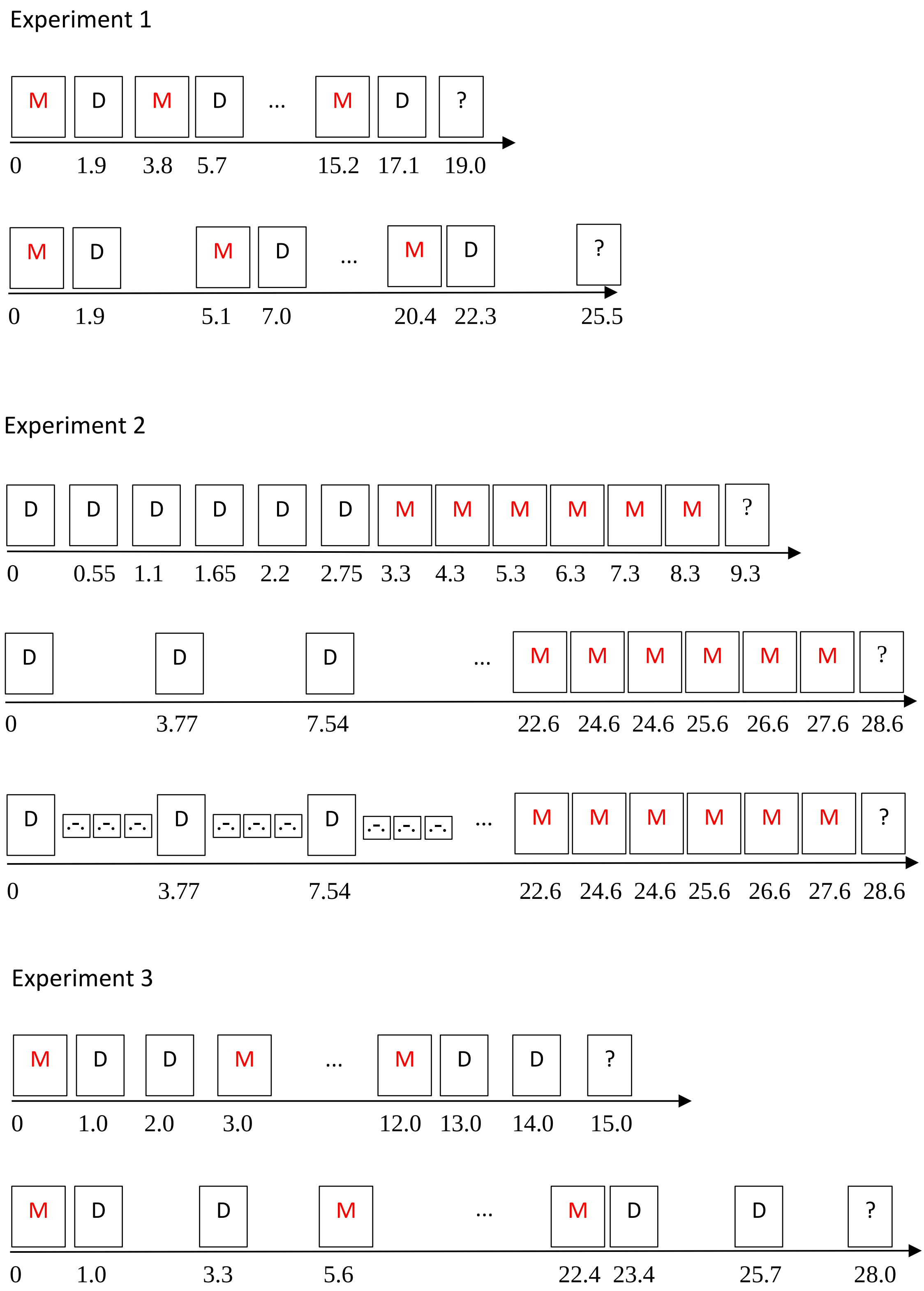


Figure 2: Time lines of events in Experiments 1 to 3, for short (first row) and long (second row) free-time intervals following distractors, and the long-filled-time intervals in

Experiment 2 (third row, with icons illustrating the spatial-fit task). Memory items are represented by a red M, and distractors by a black D. Cumulative time (in seconds) is displayed below the time arrow. For Experiment 1 these times are based on the maximum time per event; actual times were shorter to the degree that participants did not use the available 1.7 s per judgment.

Method

Participants. Twenty-seven young adults from the University of Western Australia community took part in a one-hour session in exchange for course credit.

Materials. The material consisted of a set of 506 English nouns. We selected nouns that refer to an object with relatively constant size, so that a reasonable judgment can be made as to whether it is larger or smaller than a soccer ball (this excluded words such as “box” or “stone”). The nouns spanned the size range from “ladybird” to “sun”. Some nouns referred to objects close in size to a soccer ball (e.g., “pumpkin”), so that the size judgment had an element of subjectivity. Therefore, we did not expect perfect accuracy on the size judgments.

Procedure. Each trial began with a fixation cross, replaced after 1 s by the first memory item, presented centrally on the screen in red on a white background. Participants decided whether that noun referred to an object larger or smaller than a soccer ball by pressing the right or the left arrow key, respectively. The word was displayed until a response was made, or until the maximum display duration of 1.7 s had elapsed.

Each of the five memory words was followed by one distractor word. The distractor word appeared centrally 0.2 s after offset of the preceding memory word. To distinguish the distractor from the memory item it was presented in black. Participants made size judgments on each distractor word in the same way as on the memory items. After each response – or after the maximum display duration of 1.7 s – the screen went blank for a free time period of 0.2 s (short free-time condition) or 1.5 s (long free-time condition).

After the free-time interval following the last of the 5 distractors the screen was filled with a 5 x 3 grid. Fifteen words were displayed in a random arrangement in the grid cells: The five memory items, the five distractors, and five non-presented lures. Non-presented lures were chosen at random from the word pool, excluding the 10 words used in the current trial. Participants were instructed to reproduce the memory list by clicking on the five memory items in their order of presentation. Each clicked word disappeared for 100 ms, then reappeared, and could be chosen again. After the fifth word was clicked, the screen went blank for 2 s, upon which the next trial commenced.

Participants completed three practice trials, followed by 40 test trials. Half the test trials had a consistent short free-time interval after each distractor and the other half had a long free-time interval. Trials of the two conditions were administered in a random order.

Results

We defined four categories of recall choices: (1) The correct item (*correct*), (2) one of the other four list items (*transpositions*), (3) one of the five distractors (*distractor intrusions*), and (4) one of the five non-presented lures (*NPL*). For each participant and each free-time condition we calculated the proportion of responses in these four categories, separately for each of the five list positions (i.e., for the positions in the response sequence).

We analyzed the proportions of responses in each category by a comparison of Bayesian linear mixed-effects models, computed with the BayesFactor package (Morey, 2015; Morey & Rouder, 2015) for R (R-Development-Core-Team, 2015). The BayesFactor package calculates the Bayes Factor (BF) for pairwise model comparisons, using default priors on the effect sizes of the fixed effects included in a model (Rouder, Morey, Speckman, & Province, 2012). The BF indicates the factor by which the prior odds of the compared models should be updated in light of the data to obtain the posterior odds (Berger, 2005). For instance, if a researcher has reasons to believe that a model including a main effect of variable A (Model A) is 10 times less likely than a model excluding that main effect (Model not-A), their prior odds in favor of Model A is 1/10. In light of a BF of 30, that prior odds ratio should be updated to a posterior odds ratio of $30 \times 1/10 = 30/10 = 3$, implying that in light of the data Model A is three times more probable than Model not-A. The BF reflects the relative strength of evidence in the data for one model over the other, independent of researchers' prior degrees of belief in the models. A BF of 1 reflects ambiguous evidence that favors both models equally; BFs > 1 favor Model A, and BFs < 1 favor Model not-A. The strength of evidence for Model not-A is the inverse of the BF for Model A. Bayes Factors quantify the strength of evidence on a continuous scale, and different from p-values, there is no cut-off on that scale. Following conventional interpretative guidelines (e.g., Raftery, 1995), we regard BFs between 1 and 3 as weak evidence, BFs between 3 and 10 as intermediate, and BF > 10 as strong evidence.

For each response category we started from the full model including serial position (5 levels) and free-time condition (2 levels) as well as their interaction as fixed effects. The models also included random effects of subject on the intercept as well as on the slopes of the main effects, which means that the models allowed for individual differences in the overall proportion of a response and in the size of the serial-position and the free-time main effects. The inclusion of these random effects follows the recommendation of (Barr, Levy, Scheepers, & Tily, 2013) to include a maximum of random effects in mixed-effects models.

Table 1: Bayes Factors for Linear Mixed Effects Models of Response Proportions in Experiment 1

Dependent Variable (Proportion of Responses)	Serial Position	Free Time	Serial Position x Free Time
Correct	$5.27 * 10^{29}$	1690	0.19
Transposition	$2.45 * 10^{15}$	0.57	1.69
Distractor Intrusion	$1.91 * 10^{18}$	46859	0.10
NPL	1.50	0.07	3.18

We first assessed the evidence for the interaction by comparing the full model to a model removing the interaction. Table 1 shows that the BF in favor of the model including the interaction was small for all four dependent variables, implying that there was little support in the data for any interaction between serial position and free time. For the proportion of correct responses and the proportion of distractor intrusions, the BFs < 1 provided positive evidence against the interaction (i.e., in favor of the null hypothesis that there is no interaction), the strength of which is given by the reciprocal of the BF for the interaction.

We tested for each main effect by comparing the model including both main effects (but without their interaction) to a model that excluded the main effect in question. The BFs in Table 1 provide unambiguous support for the main effect of serial position for all dependent variables, as well as for the main effect of free time on the proportion of correct responses and distractor intrusions. These effects are shown in Figure 3.

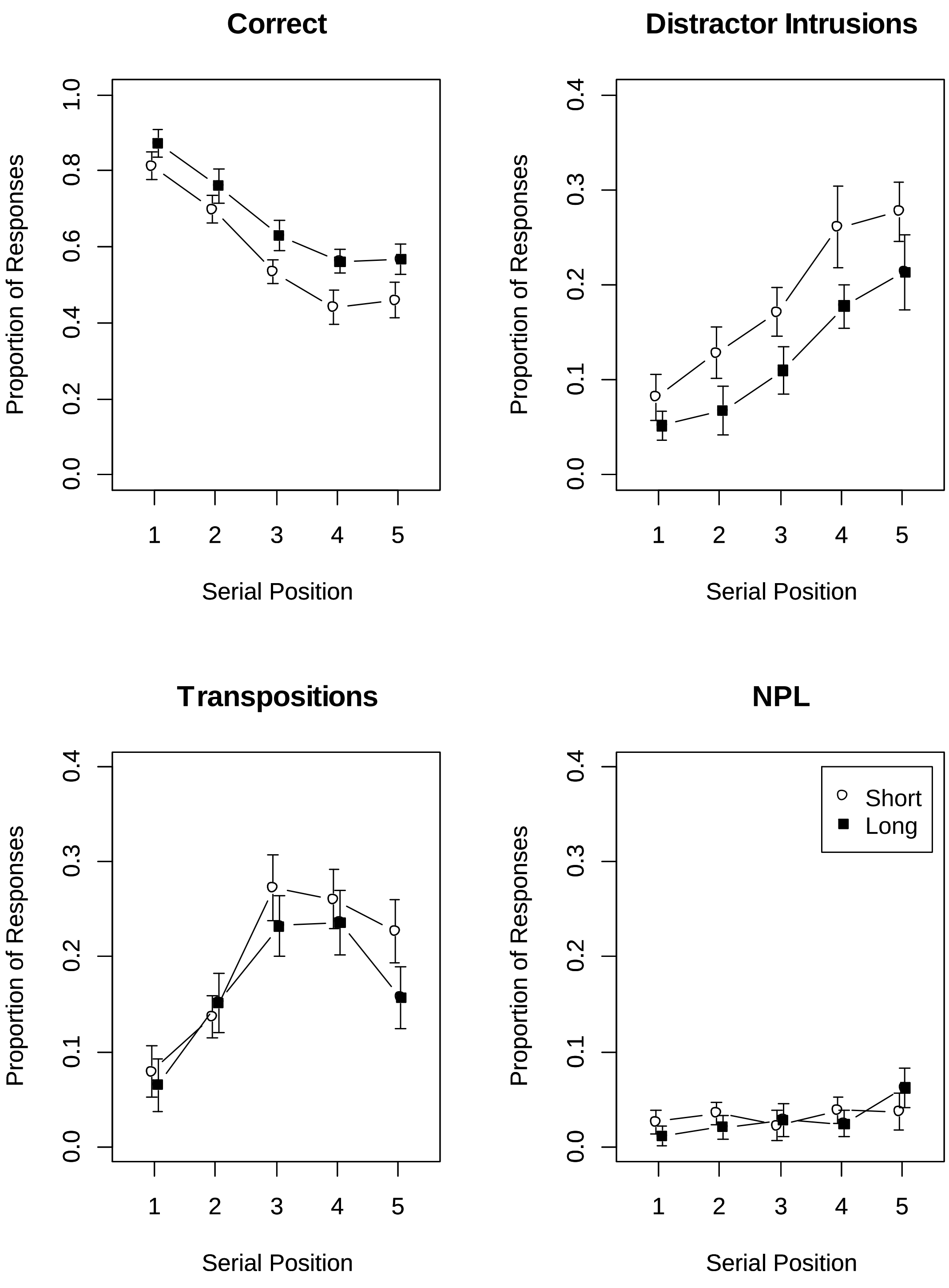
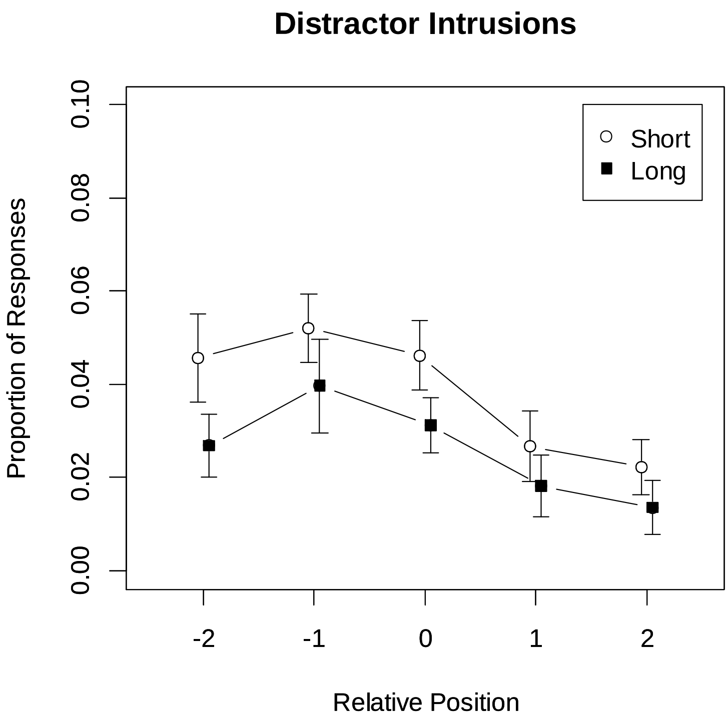


Figure 3: Proportion of response categories by serial position and free-time condition, Experiment 1. Error bars represent 95% confidence interval for within-subjects comparisons (Bakeman & McArthur, 1996)

The figure shows the typical serial-position curve of proportion correct with an extended primacy effect and a smaller, more confined recency effect. The serial-position curves for errors also replicates previous findings (e.g., Oberauer, Lewandowsky, et al., 2012): Order errors (i.e., transpositions) mirrored the serial-position curve of correct responses by an inverse U shape, whereas item errors (i.e., distractor intrusions and NPLs) increased steadily across serial positions. One novel contribution of the present experiment is the distinction of distractor intrusions and NPLs among item errors: Whereas the proportion of NPLs stayed at a low level regardless of serial position, distractor intrusions were much more prevalent and increased over serial position. Regardless of serial position, longer free time increased the proportion of correct responses (Cohen's d = 0.90) and decreased the proportion of distractor intrusions (Cohen's d = -1.47). There was no evidence for an effect of free time on transpositions, and positive evidence against a free-time effect on NPLs (Cohen's d = -.36 and -0.06, respectively).

We can use the data of Experiment 1 to test the assumption in SOB-CS that distractors are encoded by associating them to the position of the preceding item. To this end we classified distractor intrusions by their relative position to the list item they replace. Distractors replacing the immediately preceding list item are assigned relative position 0, because they are assumed to be associated to the same position as the item they replace. Distractors coming from earlier positions than the item they replace are given negative relative positions, and distractors from later in the list receive positive relative positions. For instance, think of a complex-span trial with the structure [A, d_1, B, d_2, C, d_3, D, d_4], with capital letters for memory items, and $d_{position}$ for distractors, with an index for the position to which each distractor is associated, according to SOB-CS. If the second list item, B, were replaced by d1, d2, d3, or d4, these responses would be coded as relative position -1, 0, +1, or +2, respectively. Our previous work using non-word memoranda and distractors showed that distractor intrusions peaked at relative position 0, and gradually fell off with larger positive or negative relative positions, as predicted by SOB-CS (Oberauer, Farrell, et al., 2012).

Figure 4 shows the distractor intrusions by relative position. Different from our previous findings (Oberauer, Farrell, et al., 2012), the distribution of distractor intrusions was not centered on relative position 0, but had its peak at relative position -1, indicating that people tended to replace a memory item by the distractor preceding it, rather than the distractor following it.[3]



[3] The simulation of Experiment 1 showed a similar asymmetry, though it still had a peak at relative position 0 (see Figure A2). The reason for this asymmetry is the primacy gradient of memory strength, reflected in the pronounced primacy effect for accuracy: Later list items are weaker than earlier items, making them more vulnerable to interference. In SOB-CS, the primacy gradient is a consequence of novelty-gated encoding: Later list items and distractors are less novel relative to information already encoded into working memory, and are therefore encoded less strongly. The same primacy gradient holds for distractors: Earlier distractors are stronger than later ones, making them stronger competitors at recall. As a consequence, there is a tendency for earlier distractors to intrude in later list positions, which creates the asymmetry in the relative-position curve of distractor intrusions.

Figure 4: Distractor intrusions by relative position (proportion of total responses), Experiment 1. Error bars represent 95% confidence interval for within-subjects comparisons (Bakeman & McArthur, 1996)

Discussion

The results of Experiment 1 confirm two qualitative predictions from the SOB-CS model. First, distractors were selected much more often than non-presented lures, demonstrating that distractors are encoded to some extent into working memory. This finding replicates our previous result (Oberauer, Farrell, et al., 2012) and extends it from nonwords to words. Second, longer free time following distractors improved memory performance, and reduced distractor interference. This effect is predicted from the assumption in SOB-CS that free time following a distractor is used to remove the immediately preceding distractor from working memory. Even at long free times distractor removal was far from complete, as shown by the still elevated rate of distractor intrusions. This is in contrast to the SOB-CS simulations, in which distractor intrusions were pushed down to the baseline of NPL intrusions in the long free-time condition (see Figure A1). This discrepancy suggests that distractor removal is less efficient in people than in the model.

The effect of free time is, however, open to an alternative explanation: People could use free time to rehearse or refresh the memory items, but not the distractors. As a consequence, the difference in strength between memory items and distractors in working memory might increase with longer free time, either because rehearsal or refreshing strengthens memoranda, or because distractor representations decay during the free-time interval, or both. We address different aspects of this alternative explanation in the following three experiments.

Experiment 2

In Experiment 2 all distractors preceded all the memory items (Figure 2, middle three rows). Each trial started with six distractors, followed by six memory items without further interruption by distractors. Free time following each distractor was varied. According to SOB-CS, distractors preceding the memory list should interfere with the memoranda because the distractors are encoded into working memory, and all representations held in working memory simultaneously interfere with each other. Any free time following a distractor can be used to remove that distractor from working memory, thereby reducing interference from it. This free time, however, could not be used to rehearse or refresh memoranda, because the memoranda of the current trial are presented only later. Any effect of free time on memory performance therefore cannot be attributed to selective rehearsal or refreshing of the memoranda.

With the new temporal arrangement of distractor processing and list encoding, any interference from processing on memory must be proactive. Demonstrating proactive interference from processing on memory is of interest in its own right, because apart from SOB-CS, no theory of the interplay of storage and processing in working memory predicts such an effect. Theories of behavior in the complex-span paradigm explain the detrimental effect of processing on memory maintenance by their concurrent demand on a shared resource (Just & Carpenter, 1992), by the distraction of attention from the memoranda to the distractors (Barrouillet et al., 2007; Engle, Tuholski, Laughlin, & Conway, 1999), or by the assumption that distractors displace memoranda from primary memory (Unsworth & Engle, 2007). None of these explanations apply to a situation in which memoranda are encoded only after distractor processing has finished: Distractors cannot compete for a shared resource with memoranda not yet presented; they cannot distract attention from them, and they cannot displace them from primary memory either.

The design of Experiment 2 was informed by a study reported by (Tehan & Humphreys, 1995), who demonstrated proactive interference from a first onto a second list in an immediate memory test. They observed proactive interference only when participants read the first list aloud and the second list silently. Therefore, in Experiment 2 we replaced the size-judgment task by reading aloud as the distractor processing task. Participants read each distractor aloud, following by silent reading of the memory items.

In addition to testing the effect of post-distractor free time on memory, we were interested in whether any beneficial effect of free time depends on the availability of central attention. SOB-CS is neutral on this issue, so the investigation of attentional demands of removal is exploratory, not confirmatory. Research with dual-task paradigms has shown that some central processes, including response selection and retrieval from long-term memory, strongly compete with each other, such that in most circumstances only one such process can be carried out at the same time (Pashler, 1994). This dual-task competition is attributed to a domain-general central processing mechanism, often referred to as central attention. According to SOB-CS, the free time is used to remove distractors from working memory. We aimed to test whether distractor removal requires central attention. To that end we implemented three conditions: Short free time, long free time, and long filled time. In the new long-filled-time condition participants were engaged by a second, non-verbal distractor task during the long time intervals following each distractor word they read aloud. This non-verbal task requires response selection and therefore should engage central attention. If distractor removal requires central attention, it should be less successful in the long-filled-time condition than in the long-free-time condition, and that should be reflected in worse memory performance and more distractor intrusions.

Method

Participants. Seventy-nine students from University of Zurich took part in a single one-hour session. They were reimbursed with 15 Swiss Francs (about 15 USD) or partial course credit. Data from six participants were excluded because their memory performance was exceptionally poor (< 25% correct).

Materials and Procedure. Memoranda, distractors, and non-presented lures were drawn at random from a pool of 676 German nouns. The nouns were between four and six letters long and consisted of one or two syllables. We shuffled the order of words for each participant and selected the 18 words needed for each trial by peeling off the next 18 words in that order, returning to the beginning of the random shuffle only once the pool was exhausted. In this way, no word was used repeatedly within 37 trials.

Each trial began with a fixation cross, which was replaced after 2 s by the first distractor word. Each distractor word was presented centrally on the screen for 500 ms in black; participants were instructed to read these words aloud, and their speech was recorded through the microphone of a headset. In the short-free-time condition, each distractor word was followed by the next distractor word, or the first memory item, after 50 ms. In the other two conditions, a longer interval followed each distractor word, which was either unfilled or was filled with three instances of a spatial judgment task. In this task, borrowed from (Vergauwe, Barrouillet, & Camos, 2009), participants decided whether a horizontal bar fit into the gap between two blocks presented above or below the bar. The same time interval followed each distractor word in the two long-time conditions; its duration was determined to allow for three spatial judgments, as follows: From a previous experiment using the spatial-judgment task in the context of a complex-span paradigm (Oberauer & Lewandowsky, 2014) we obtained the mean response times for the first three spatial judgments preceding presentation of a memory list (0.67, 0.54, and 0.56 s). These times were multiplied with 1.7 to obtain the available time for each size judgment (i.e., 1.22, 0.99, and 1.01 s). A factor of 1.7 was chosen to obtain available time intervals within which participants could complete most judgments, but have little free time to spare. In the long-filled-time condition, three spatial-judgment stimuli were presented one by one, starting 50 ms after the offset of the distractor word. Each stimulus was displayed until a response was recorded, or until the available time for that judgment had elapsed. The next stimulus was presented at the end of the available time for the preceding judgment. In the long-free-time condition, a blank screen followed each distractor word for a duration equal to the sum of the time intervals for the three spatial judgments. In this way, the time between successive distractor words was exactly equated between the long-free-time and the long-filled-time conditions (i.e., 0.05 + 1.22 + 0.99 + 1.01 = 3.27 s). Figure 2 shows the time lines for the three conditions.

After the end of the last post-distractor interval, the six memory items were presented in red for 1 s each, with no more than a single screen-refresh cycle between them. Participants were instructed to read these words silently and remember them in order. Following the last memory item, 18 probe words were displayed in a random arrangement in a 5 x 4 matrix, leaving empty the left and right cells of the bottom row. The 18 probe words consisted of the six memory words, the six distractor words, and six non-presented lures. Participants reproduced the memory list by clicking on the words in their order of presentation; once a word was clicked, its frame was briefly marked red and then returned to black.

Because we wanted to make sure that participants were fully prepared for the spatial judgment task we ran the three conditions in a blocked order, counterbalanced across participants. Each block consisted of 2 practice trials, followed by 16 test trials.

Results

We analyzed the proportions of correct responses, transpositions, distractor intrusions, and NPLs as a function of serial position and time condition (short free time, long free time, and long filled time), using a series of Bayesian linear mixed-effects model comparisons as described in connection with Experiment 1. Table 2 summarizes the BFs for the model comparisons. In addition to the effects of serial position, there was a clear effect of time on proportion correct and on distractor intrusions. As shown in Figure 5, longer free times following distractors resulted in more correct responses and fewer distractor intrusions than short free times. For both dependent variables, the data for the long-filled-time condition fell in between the other two time conditions. There was also an (albeit smaller) main effect of time on transpositions and on NPLs. There was clear evidence against any interaction of serial position and time condition (all BF $\ll 1$).

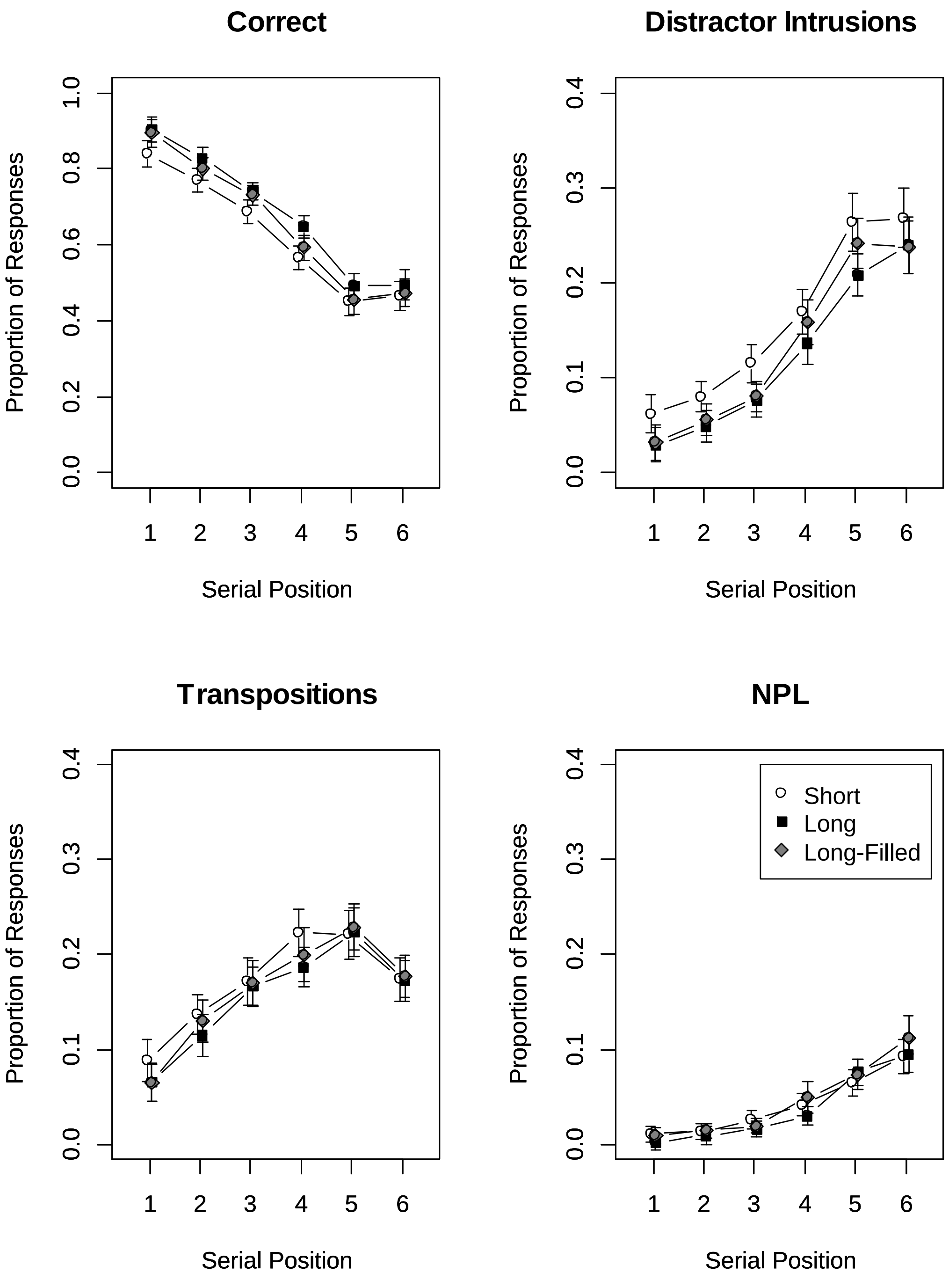


Figure 5: Proportion of response categories by serial position and free-time condition, Experiment 2. Error bars represent 95% confidence interval for within-subjects comparisons (Bakeman & McArthur, 1996)

Table 2: Bayes Factors for Linear Mixed Effects Models of Response Proportions in Experiment 2

Dependent Variable (Proportion of Responses)	Serial Position	Time	Serial Position x Time
Correct	$1.27 * 10^{88}$	13031	0.005
Transposition	$2.81 * 10^{33}$	68	0.001
Distractor Intrusion	$2.06 * 10^{72}$	345108	0.0006
NPL	$7.48 * 10^{43}$	20	0.004

We decomposed the effect of time condition by pairwise comparisons using Bayesian t-tests. The results can be found in Table 3. The pairwise comparisons of short and long free times confirmed that longer free time led to better recall and fewer distractor intrusions (d = 0.46 and -.51, respectively). The comparisons of the long-filled condition with each of the other two time conditions revealed ambiguous evidence, with BFs too close to 1 to allow any firm conclusion (d = .20 and -.30 for long-filled vs. short, and d = .24 and -.16 for long vs. long-filled).[4] We had obtained similarly ambiguous evidence after initially testing a smaller number of participants, and therefore gradually increased the sample (which, unlike with frequentist statistics, is legitimate in a Bayesian framework; Rouder, 2014; Wagenmakers, 2007), but the ambiguity remained. The question whether a filled interval is less effective than an unfilled interval must thus remain open for now.

[4] Although the effect size of the comparison of short and long free times is the sum of the effect sizes of long-filled vs. short, and of long-free vs. long-filled, the former was large enough to receive unambiguous statistical support, whereas neither of the latter two was. This reflects the fact that Bayes Factors increase steeply with increasing set size once the set size exceeds ambiguous values (see Wetzels et al., 2011, for illustrative examples)

Table 3: Bayes Factors from T-Tests for Pairwise Comparisons of Time Conditions in Experiment 2

Dependent Variable (Proportion of Responses)	Short vs. Long	Short vs. Long-Filled	Long vs. Long-Filled
Correct	53.2	0.46	0.80
Transposition	1.6	0.18	0.40
Distractor Intrusion	166.8	2.27	0.29
NPL	0.14	0.20	0.19

Discussion

Our second experiment provided unambiguous evidence for proactive interference of distractor processing on immediate memory: Distractor intrusions were much more prevalent than intrusions of non-presented lures. This finding confirms once more the assumption in SOB-CS that distractor processing leads to encoding of distractor representations into working memory. Distractor intrusions were reduced, and memory accuracy improved, by longer free time following each distractor, as predicted from the assumption in SOB-CS that free time is used to remove distractors from memory.

These findings are difficult to explain for other theories of how working memory is affected by concurrent processing. One popular assumption is that processing impairs memory because it disrupts rehearsal (Towse, Hitch, & Hutton, 2000) or refreshing (Barrouillet et al., 2007). In particular, the beneficial effect of free time in between distractors has been explained as reflecting the effect of refreshing during free time (Barrouillet et al., 2007). These explanations do not apply to the present experiment, because there is nothing to rehearse or refresh during the entire distractor-processing episode. Another approach is to assume that distractor processing draws away attention from the memoranda (Engle et al., 1999), or that it displaces memoranda from primary memory (Unsworth & Engle, 2007). Again, these explanations cannot apply to the present situation in which no memoranda have been presented at the time the distractors are processed. Our findings do not imply that these alternative explanations are wrong, but that they are incomplete: The adverse effect of distractor processing on memory in conventional complex-span could still be *partly* due to the prevention of rehearsal/refreshing, or to the distraction of attention or displacement from primary memory, but none of these contributions can account for the effect observed here, so they are unlikely to account *completely* for the effect of distractor intrusions in standard complex span tasks.

The results of Experiment 2 taken in isolation could be explained by a temporal-distinctiveness model such as SIMPLE (Brown, Neath, & Chater, 2007). In temporal-distinctiveness theories, contents in episodic memory are accessed through their temporal context. The probability that another than the searched-for content is erroneously retrieved decreases with the distance of the two contents on the temporal context dimension. Longer free time between distractors in Experiment 2 separates all distractors more in time from the subsequent list, thereby reducing the probability that they intrude into recall. Temporal-distinctiveness models, however, cannot easily explain the free-time benefit in the standard complex-span task (such as our Experiment 1), because when memory items and distractors are interleaved, longer free time implies that the memory items recede more into the past, rendering them temporally less distinctive (see Appendix B for a confirmation through simulation).

One might nonetheless construct an alternative ad-hoc explanation of our results of Experiments 1 and 2 along the following lines: Distractors are encoded into working memory, and hence they interfere with subsequent memoranda, but they are not removed during free time. Rather, they just decay over time, and therefore become weaker with longer free-time intervals. Experiments 3 and 4 were designed to test the assumption of distractor decay.

Experiment 3

If distractor representations decayed over time, then the tendency of any distractor to intrude should decrease with time passing since the processing – and hence encoding – of that distractor. More formally, the probability of a distractor encoded at time t_E to intrude in a test at time t_T should decrease as the time interval Δt between t_E and t_T increases. The time interval relevant for decay, Δt, is the entire interval between t_E and t_T, not just the free time following distractors. The purpose of Experiment 3 was to test this prediction by varying Δt over a large range.

The first two experiments were not well suited for this purpose because Δt was confounded with other variables. In Experiment 1, the time of distractor processing was confounded with the serial position of item encoding and of item recall. Because distractor intrusions tend to replace items in their close temporal neighborhood (i.e., items preceding or following the distractor), distractors encoded early are also most likely to intrude early in the recall sequence, so that the time between distractor encoding and the occurrence of a distractor intrusion varies little across list positions. Moreover, the strong primacy effect in forward serial recall implies that there are relatively few errors in early positions, leaving little room for distractor intrusions. This alone would lead to more intrusions of distractors from anywhere in the list occurring towards the end of the recall sequence – that is, at higher values of Δt – thereby potentially obscuring an effect of decay on distractor intrusions. In Experiment 2, the time of distractor processing was confounded with the distractor's temporal proximity to the memory list. If encoding of distractors involves associating them to temporal contexts (Brown et al., 2007) or to episodic contexts (Farrell, 2012), these contexts are more likely to overlap with the memory list for later-presented distractors. This would lead to more intrusions of later than of earlier distractors, generating an effect of Δt that looks like distractor decay even if there is no decay.

In Experiment 3 we deconfounded the serial position of item presentation (input) and test (output) by using a random-probed recall paradigm (Oberauer, 2003). Memory items were presented from left to right across a row of boxes, and participants read them aloud. After presentation of each item (in red), two distractor words were presented (in black) one by one in the same box as the preceding item; participants also had to read these words aloud. Memory was tested by probing the five input boxes in a new random order for each trial. In this way, input and output order were uncorrelated across trials. Critically for the present purpose, this procedure also deconfounded the order of distractor processing from the order of testing. We can now assess the effect of time on distractor intrusions over a large range of Δt values while minimizing confounds with input and output position: For any given output position distractors processed early (resulting in longer Δt) and distractors processed late in the input sequence (resulting in shorter Δt) have an equal a-priori chance of intruding because a given output position is equally likely to test items in any input position. Likewise, any given distractor has an equal chance of intruding in an early or a late output position, because that distractor's input position is equally likely to be tested at any output position.

Method

Participants. Twenty-four students of the University of Zurich took part in two one-hour sessions in exchange for 30 Swiss Francs or partial course credit. One participant's data were excluded because of exceptionally bad memory performance (< 20% correct).

Materials and Procedure. Memory items and distractors were sampled at random from the same pool of German words as in Experiment 2. Each trial began with the display of a row of five boxes across the upper quarter of the screen. The five memory items were displayed in red in these boxes from left to right; each memory item was followed by two distractors presented in black in the same box. Each word – memory item or distractor – was presented for 0.8 s. Memory items were always followed by a 0.2 s blank interval. Distractors were followed by a blank free-time interval that varied between trials (short: 0.2 s, long: 1.5 s). The time line of events is shown in the bottom two rows of Figure 2. Participants were instructed to read each word aloud and remember the red words.

After the final distractor, a 3 x 5 matrix was displayed in the lower three quarters of the screen, below the (now empty) 5 boxes denoting the input positions. The matrix contained, in random arrangement, the five memory words, five distractors (one randomly chosen distractor from the pair of distractors following each item), and five NPLs. A red question mark was displayed in one randomly selected input box at the top of the screen, prompting participants to select the memory item they had seen in that box from the 3 x 5 matrix below. All five input boxes were probed in this way in a new random order for each trial.

In each of the two sessions participants worked through 25 short and 25 long free time trials in random order.

Results

Our first analysis mirrors the analyses of the preceding experiments, looking at effects of free time and input serial position. These results are plotted in Figure 6 for the four categories of responses, and the corresponding Bayes Factors can be found in the upper section of Table 4. There was again a clear effect of free time (Cohen’s d = 1.49, -1.61, -0.61, and -0.41, for correct, transpositions, distractor intrusions, and NPLs, respectively). Different from the preceding experiments, the effect was more apparent in transposition errors than distractor intrusions. The effect of serial position was represented by a largely symmetric U-shaped curve for proportion correct, and a corresponding inverse-U-shaped effect on transposition errors and distractor intrusions. The symmetry of the serial position curve with a random test order has been observed previously (Oberauer, 2003). The proportion of NPL errors appears largely unaffected by serial position and free time.

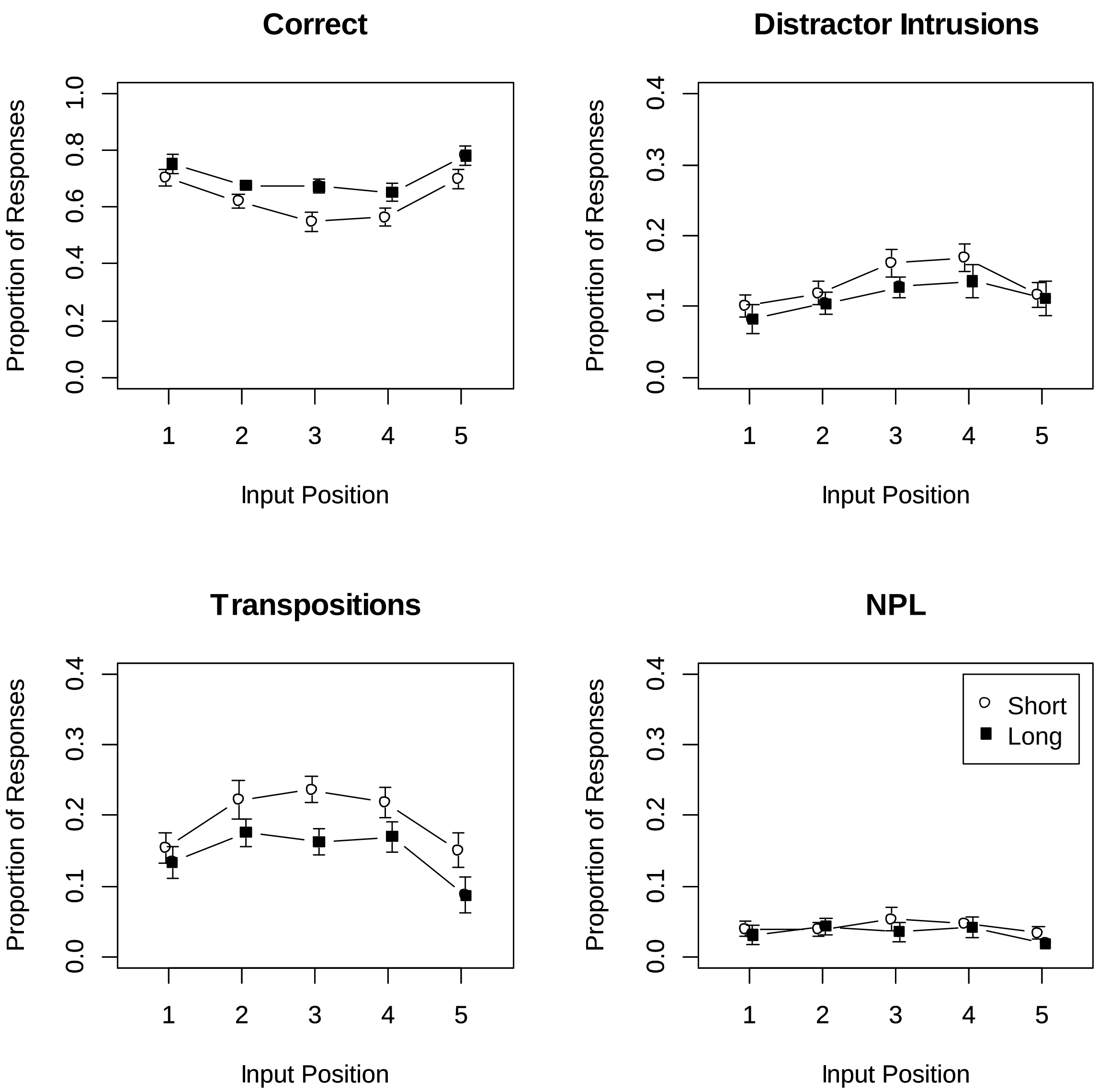


Figure 6: Proportion of response categories by input serial position of the tested item and free-time condition, Experiment 3. Error bars represent 95% confidence interval for within-subjects comparisons (Bakeman & McArthur, 1996).

Table 4: Bayes Factors for Linear Mixed Effects Models of Response Proportions in Experiment 3

Dependent Variable (Proportion of Responses)	Serial Position	Free Time	Serial Position x Free Time
Serial Position = Input Position			
Correct	$2.1 * 10^9$	$4.1 * 10^4$	11.7
Transposition	$7.9 * 10^6$	$8.6 * 10^3$	0.50
Distractor Intrusion	$2.1 * 10^4$	3.3	0.13
NPL	0.67	0.75	0.19
Serial Position = Output Position			
Correct	$6.6 * 10^6$	$4.1 * 10^4$	0.20
Transposition	0.06	$2.4 * 10^4$	0.27
Distractor Intrusion	$4.5 * 10^3$	3.1	0.20
NPL	0.01	0.70	0.09

In the random-probed recall paradigm, input and output position are uncorrelated, so that we can assess the effect of output position separately from that of input position. The proportion of responses in the four response categories over output position is shown in

Figure 7, and the corresponding BFs can be found in the bottom half of Table 4. It is clear that accuracy declined over output position, confirming the effect of output interference. Notably, whereas transposition errors remained constant across output position, distractor intrusions and NPL errors increased. The increase of distractor intrusions over output position is the opposite of what is predicted by distractor decay. If distractors decay, their prevalence should decline over output position relative to the prevalence of other errors, because the strength of distractor representations declines, whereas the strength of representations giving rise to other errors (i.e., transpositions, arising from the strength of memory items other than the tested one, and NPLs, arising from the constant baseline strength of extra-trial stimuli) does not decline to the same extent over output position. For these reasons, the pattern of error types over output position already questions the notion of distractor decay.

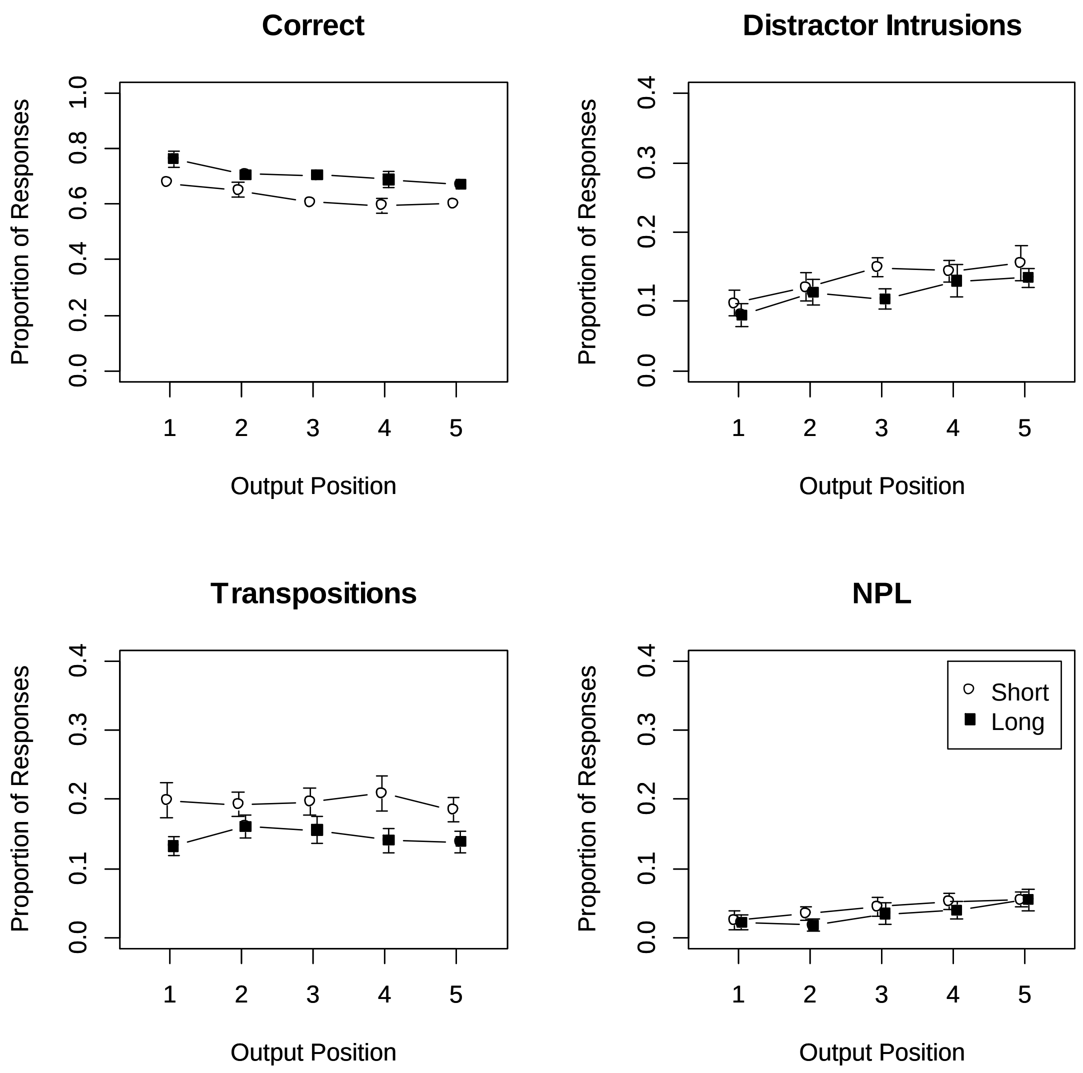


Figure 7: Proportion of response categories by output serial position and free-time condition, Experiment 3. Error bars represent 95% confidence interval for within-subjects comparisons (Bakeman & McArthur, 1996)

For a more comprehensive test of the distractor decay hypothesis we tested the effect of Δt, the time interval between encoding a distractor and the time of a test, on the probability of a distractor to intrude at that test. The first step of this analysis was to construct the input-output matrix of distractors for each participant. For each combination of input position *i* with output position *o* we counted the number of distractors originating in input position *i* that were selected for recall in output position *o*. Note that the input position of the distractor is not necessarily the same as the input position of the item that was tested, which defines the x-axis of the plots in Figure 6. For instance, the item in input position 2 could be tested in output position 4, and the person chooses a distractor that had been processed in position 5. For Figure 6, this response counts towards the distractor intrusions in the item's input position 2. In contrast, for the present construction of the input-output matrix we count it towards distractor intrusions from input position 5. The distractor input-output matrix of each participant and condition was divided by the number of trials to obtain the proportion of responses that were distractors from each input position, occurring in each output position. The left part of Table 5 shows the proportional distractor input-output matrices for each free-time condition, averaged across participants.

Table 5. Distractor Input-Output Matrices and Corresponding Δt Values by Free-Time Condition, Averaged over Participants, Experiment 3

	P(Distractor Intrusions) Output Position					Δt (s) Output Position				
Input Position	1	2	3	4	5	1	2	3	4	5
Short Free Time										
1	.024	.019	.023	.025	.028	11.5	17.6	22.5	26.7	30.6
2	.014	.020	.023	.018	.024	8.6	14.8	19.6	23.8	27.7
3	.025	.029	.029	.026	.032	5.8	11.9	16.7	20.9	24.8
4	.023	.026	.042	.032	.044	2.9	9.0	13.9	18.0	22.0
5	.012	.027	.032	.042	.026	0	6.1	11.0	15.2	19.1
Long Free Time										
1	.015	.019	.014	.028	.031	21.5	27.1	31.8	35.9	39.7
2	.013	.014	.020	.020	.027	16.1	21.8	26.4	30.5	34.4
3	.015	.029	.024	.020	.021	10.7	16.4	21.0	25.2	29.0
4	.020	.028	.023	.035	.025	5.3	11.0	15.7	19.8	23.6
5	.017	.022	.022	.027	.030	0	5.6	10.3	14.4	18.3

We constructed an analogous input-output matrix for Δt values for each participant and condition by determining the average Δt for each cell of the input-output matrix. The Δt for cell [i, o] was the calculated as

$$\Delta t(i,o) = (N - i)(t_p + 2t_d) + \sum_{j=1}^{o-1} RT_j$$

with N for the number of items in the list (i.e., 5), t_p for the presentation time per item (1 s), t_d for the distractor processing duration, including free time (i.e., 1.0 s for the short free time condition, and 2.3 s for the long free time condition), and RT_j the mean response time for output position j. The first part of the sum represents the time between processing a distractor in input position i and the end of list presentation (including distractor processing). The second part of the sum represents the duration of the o-1 recall events preceding a test in output position o. The right part of Table 5 presents the Δt for each input-output cell averaged across participants.

To determine the effect of Δt on the probability of a distractor intrusion we ran a hierarchical Bayesian regression with a binomial link function (Kruschke, 2011), using the Δt values for each input-output cell and the contrast-coded free-time condition as predictors for the proportion of distractor intrusions as criterion. The model is given by the following equations (read "~" as "is distributed according to"):

$$y_{j,c,i,o} \sim Binomial(\theta_{j,c,i,o}, n_{j,c})$$
$$\theta_{j,c,i,o} = \frac{\exp(a_j + b1_j \Delta t_{j,c,i,o} + b2_j C_c)}{1 + \exp(a_j + b1_j \Delta t_{j,c,i,o} + b2_j C_c)}$$
$$a_{j,c} \sim Normal(\mu_a, \sigma_a)$$
$$b1_{j,c} \sim Normal(\mu_{b1}, \sigma_{b1})$$
$$b2_{j,c} \sim Normal(\mu_{b2}, \sigma_{b2})$$

Here, $y_{j,c,i,o}$ represents the criterion variable, that is, the number of distractor intrusions for person j in condition c in cell [i,o]. Parameter $\theta_{j,c,i,o}$ is the estimated probability of that distractor intrusion, and $n_{j,c}$ is the number of trials of person j in condition c. The θ values are modeled as a logistic function of the linear combination of predictors Δt and C (for free-time condition), both of which were centered on zero. The regression parameters were assumed to be normally distributed across subjects with means μ_a (for the intercept), μ_{b1} (for the slope of Δt), and μ_{b2} (for the slope of free-time condition C), and corresponding standard deviations parameters σ. We used normal priors (mean = 0, precision = 0.01) for the three μ parameters and Gamma priors (shape = 1, rate = 0.01) for the σ parameters.[5]

Figure 8 shows the results. The top panel plots the proportions of distractor intrusions as a function of Δt values, separately for each free-time condition. It is clear that there is no tendency for distractor intrusions to decline over increasing time between encoding and test. The bottom two panels of Figure 8 show the posterior probability density of the mean effects of Δt (expressed as the predicted change in the proportion of distractor intrusions for a 10 s change in Δt) and of free-time condition. The predicted effect of Δt was slightly positive, implying that there might be a small tendency of distractors to intrude more the longer they have been held in WM, though that effect is fairly uncertain because its 95% credible interval includes zero.[6] The effect of free-time condition was unambiguously negative, with a 95% credible interval excluding zero, confirming our previous conclusion that longer free time led to fewer distractor intrusions.

[5] Normal priors were used for parameter means because they can assume values on the entire real line; with a mean of 0 the prior is neutral about the parameter's polarity. Gamma priors were used for SD parameters because they must be positive. Both prior distributions were so broad as to be largely uninformative (Kruschke, 2011)

[6] The 95% credible interval (a.k.a. 95% highest-density interval) is the smallest interval that covers 95% of a parameter's posterior density, implying that the true value of the parameter lies within that interval with p = .95.

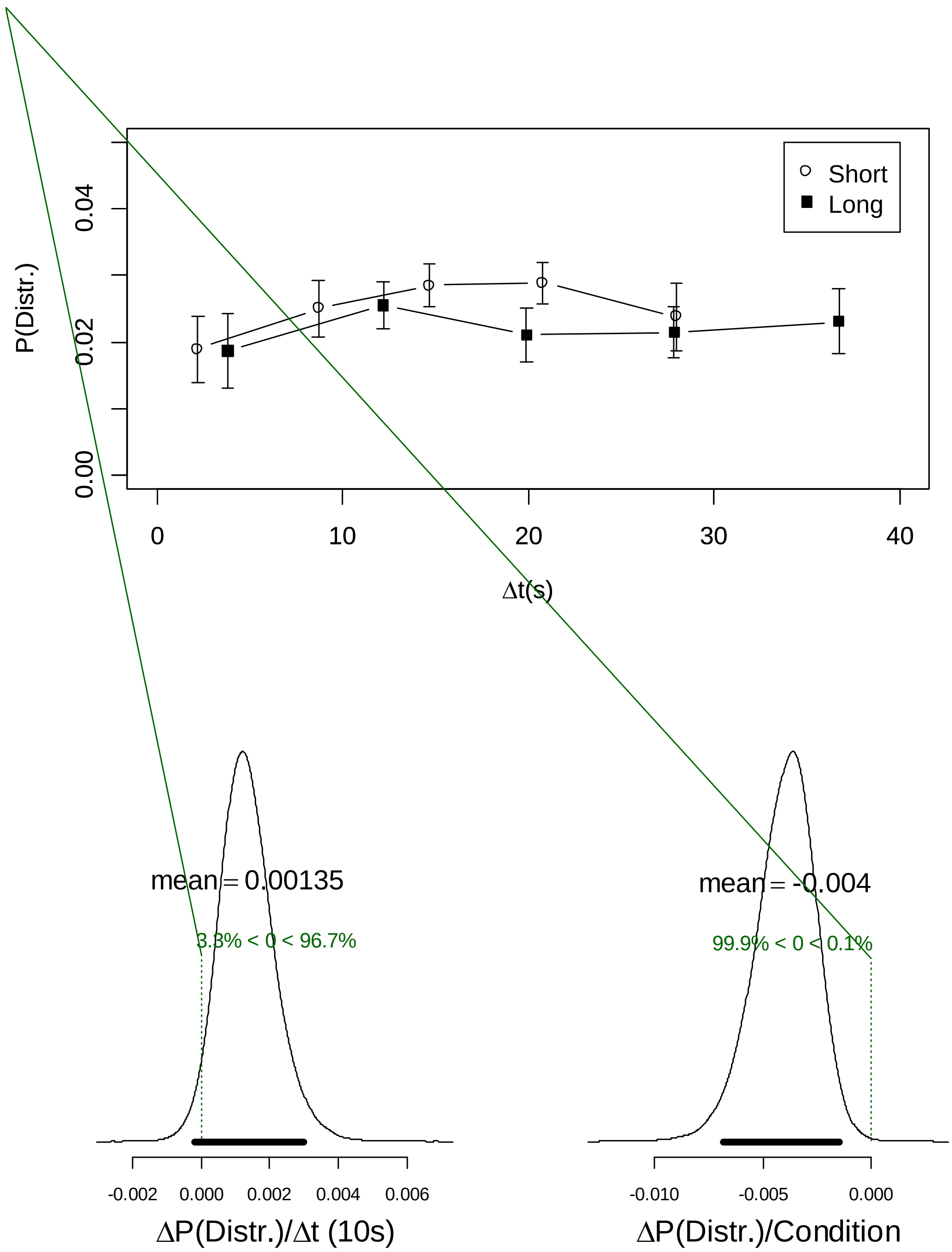


Figure 8: Top: Proportion of distractor intrusions as a function of the time between encoding of a distractor and the test at which it intrudes, Δt, in Experiment 3. Data were aggregated for plotting into five bins of Δt; error bars represent 95% confidence intervals for within-subjects comparisons. Bottom: Posterior probability densities for changes in the probability of distractor intrusions as a function of Δt and of free-time condition as implied by the posterior densities of the regression parameters.

One could object that our analysis still confounds Δt with the strength of memory items tested. For instance, the shortest Δt arises from the combination of the last input position with the first output position: For this cell, accuracy is expected to be high because of the primacy gradient over output position, leaving relatively little room for a distractor intrusion. To remove any potential impact of different accuracy levels for different levels of Δt, we re-ran the regression analysis using as criterion not the proportion of distractor intrusions among all responses, but the proportion of distractor intrusions among error responses. The proportion of distractor intrusions among all error responses estimates the conditional probability that an error is a distractor intrusion, given that an error is committed, and as such it is independent of the recall accuracy at a given level of Δt. This regression analysis led to the same conclusion as the one presented above: The regression weight for Δt was negligible, with a 95% credible interval clearly including zero.

Our final analysis asks again whether, as predicted by SOB-CS, distractors tended to replace the memory items immediately preceding them, that is, items that had been presented in the same input position, Figure 9 shows distractor intrusions by their relative position, computed over input position in the same way as for Experiment 1. Distractor intrusions were most prevalent at relative position 0, showing that distractors tended to replace items that immediately preceded them in in the input sequence, and were presented in the same boxes. This is as predicted from the assumption in SOB-CS that distractors are bound to the same context as the preceding memory item. The effect of relative position was statistically confirmed by BF = 58.0 in favor of the main effect.

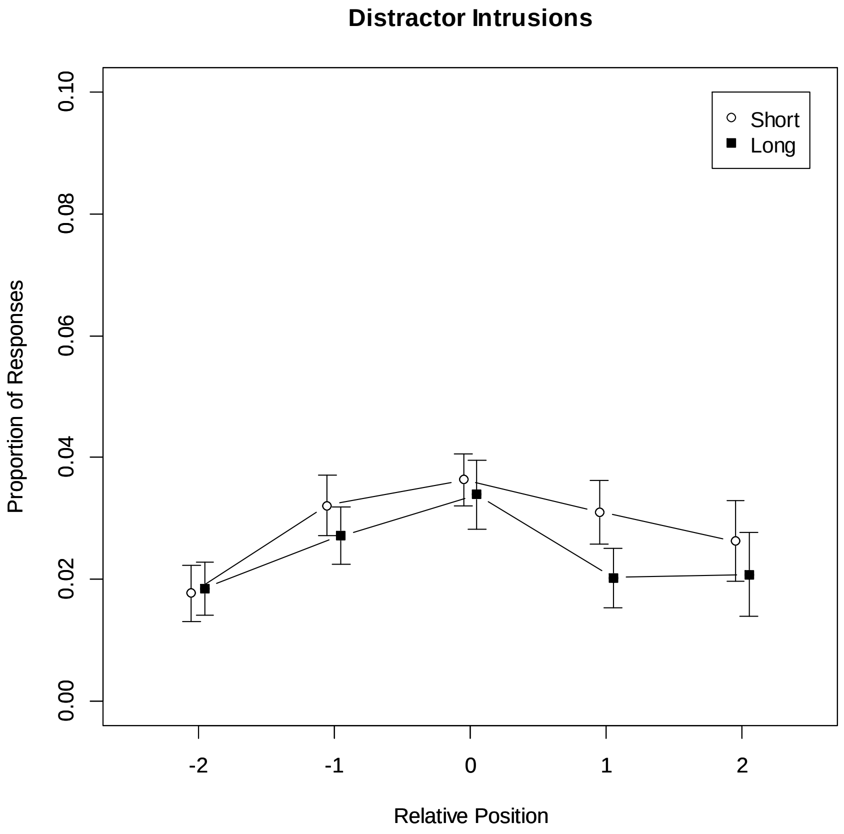


Figure 9: Distractor intrusions by relative position (proportion of total responses), Experiment 3. Error bars represent 95% confidence interval for within-subjects comparisons (Bakeman & McArthur, 1996)

Discussion

Experiment 3 replicated the beneficial effect of free time with a probed-recall paradigm. It also replicated the serial-position effects of previous experiments that de-confounded input and output order (Cowan, Saults, Elliott, & Moreno, 2002; Oberauer, 2003): There were largely symmetrical primacy and recency effects over input position, and a gradual decline of performance over output position. Our fine-grained analysis of errors shows that output position exclusively affected item errors, not order errors (i.e., transpositions). In addition, Experiment 3 provided support for the prediction of SOB-CS that distractors tend to intrude by replacing the items in the same input position (i.e., relative position 0 in Figure 9).

Our main question for this experiment was whether distractor intrusions tended to decline over time, and if so whether that tendency could explain the free-time effect. That was clearly not the case. When we analyzed the proportion of distractor intrusions as a function of the time between encoding and test, we found clear evidence against a decline of distractor intrusions over time. Only about 4 percent of the posterior density of the effect of Δt was below zero (see Figure 8, bottom left). Moreover, the regression model confirmed the effect of free time on distractor intrusions while statistically controlling the effect of overall time the distractor spent in working memory, as measured by Δt. Longer free time following distractors resulted in fewer distractor intrusions (and better overall memory), and that effect cannot be explained by a tendency of distractor intrusions to continuously decline over time for their entire duration in working memory.

Experiment 4

Experiment 4 provides a further test of distractor decay. This experiment again used the random-probed recall procedure. The only experimental manipulation – besides serial position – was the duration of an unfilled retention interval between list presentation and test (0 vs. 5 s). If distractors decayed over an unfilled interval, while memory items are selectively rehearsed or refreshed, then there should be fewer distractor intrusions, and better memory performance, after a longer retention interval. We chose a 5 s interval to match the total free time added in the long free-time condition of our previous experiments. If the beneficial effect of that added free time were due to distractor decay, then we should see an equally strong beneficial effect from inserting the same duration of free time between list presentation and recall. In contrast, the SOB-CS model predicts little, if any, beneficial effect of an extended retention interval, because SOB-CS can remove only the last-encoded representation from working memory (Oberauer, Lewandowsky, et al., 2012). This is because removal relies on Hebbian anti-learning, which weakens the association between a distractor and the context it was bound to. This mechanism requires an active representation of the distractor and the context in the network, which is available only immediately after the distractor has been processed and encoded. Therefore, the retention interval could only be used to remove the very last distractor.

Method

Participants. Thirty-five students from University of Zurich took part in two one-hour sessions in exchange for 30 Swiss Francs or partial course credit. Data from two participants were removed because of exceptionally bad performance (accuracy < 20%).

Materials and Procedure. The experiment was identical to Experiment 3 with two exceptions: First, the free time following distractors was always short (0.2 s). Second, on a random half of all trials, a 5 s unfilled retention interval was inserted between the last distractor and the presentation of the test matrix.

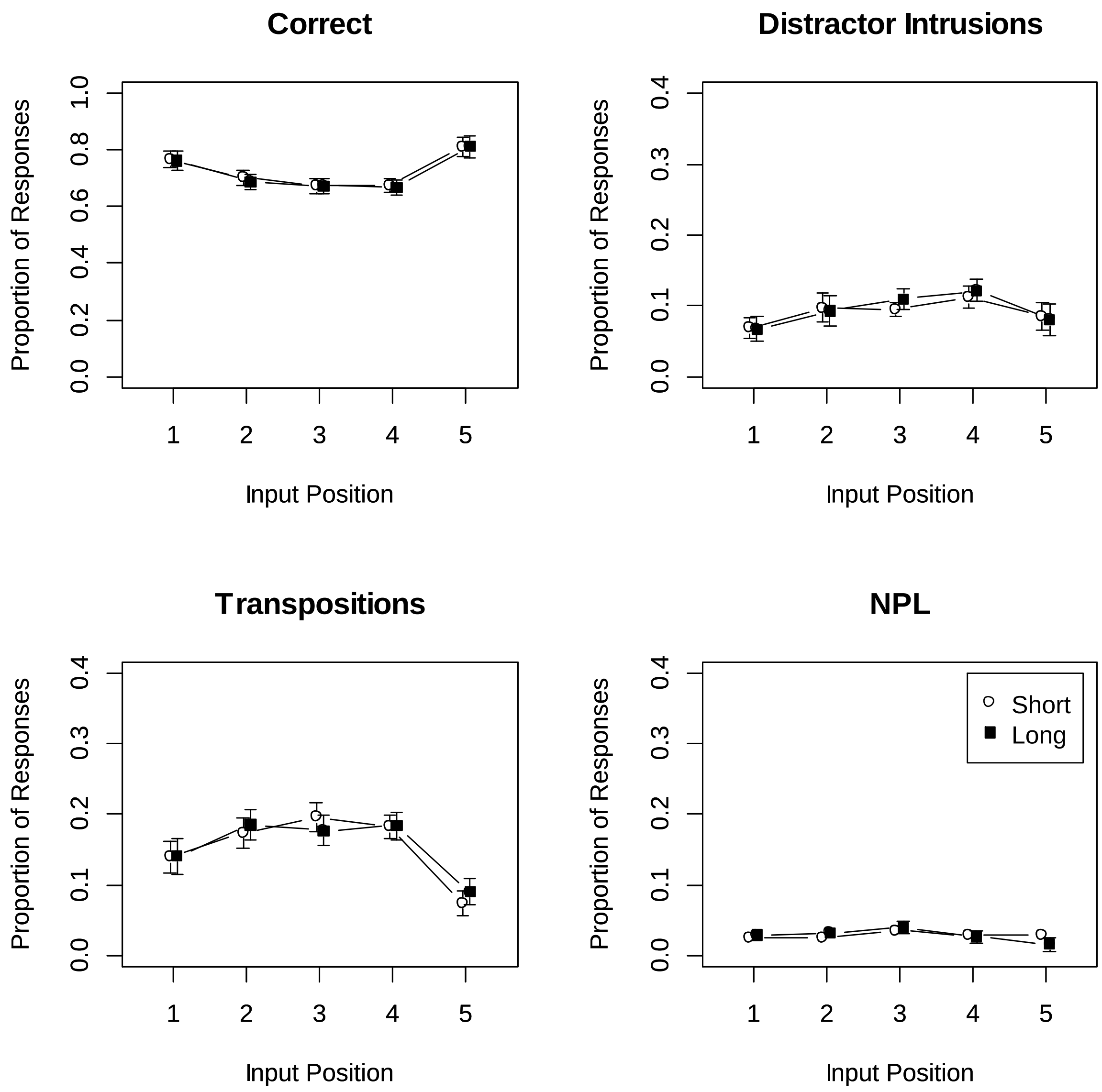


Figure 10: Proportion of response categories by input serial position of the tested item and retention-interval condition, Experiment 4. Error bars represent 95% confidence interval for within-subjects comparisons (Bakeman & McArthur, 1996).

Results

Figure 10 shows the proportion of response categories by input serial position and retention interval. The serial-position effects replicated those of Experiment 3. More pertinent to our question, there was no hint of an effect of retention interval on any response category

(Cohen's d = -0.10, -0.05, 0.08, and 0.02, for correct, transpositions, distractor intrusions, and NPLs, respectively). The BFs in the upper part of Table 6 show that the data provide evidence against a retention-interval effect – the strength of that evidence is given by the reciprocal of the BFs in favor of the effect (the latter being reported in the table). Of greatest theoretical interest is the effect of retention interval on distractor intrusions; the posterior density of that effect, plotted in Figure 11, is narrowly concentrated on zero, with a very slight tendency towards positive values, which reflect an *increase* of distractor intrusions with the longer retention interval. The BF in favor of the null hypothesis reported in Table 6 reflects a two-tailed test, comparing the null model to a model with an effect in either direction. The decay hypothesis, however, entails a directed prediction: Distractor intrusions should decline with a longer retention interval. We therefore carried out a one-tailed Bayesian t-test to test this hypothesis, comparing a model with the predicted negative effect against a model assuming either no effect or a positive effect (Morey & Wagenmakers, 2014). The BF in favor of the negative effect was 0.082, implying a BF of 1/0.082 = 12.2 *against* the negative effect predicted from distractor decay.

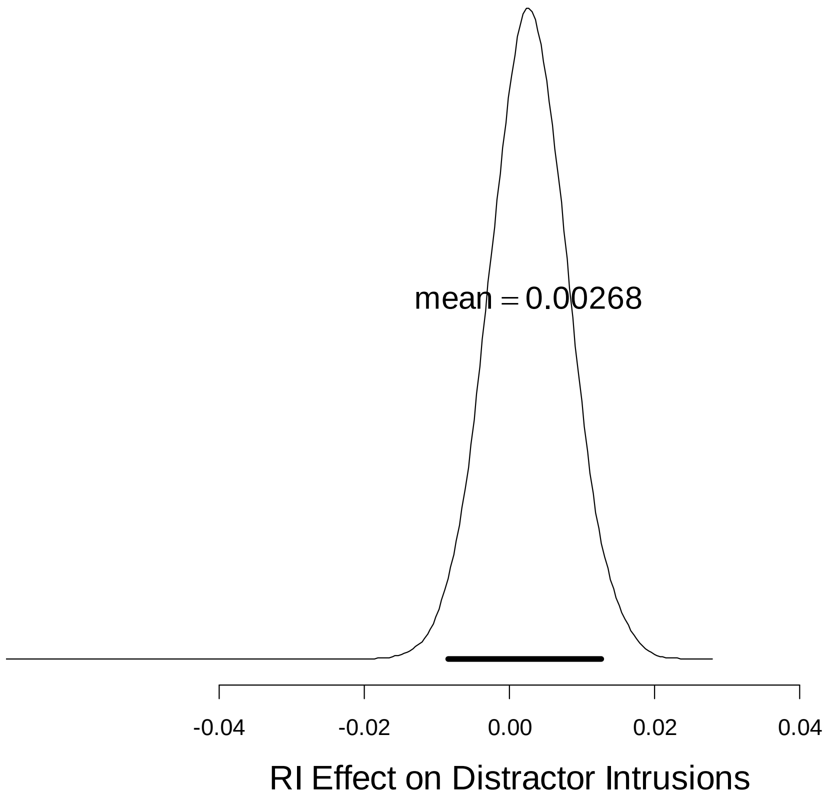


Figure 11: Posterior probability density of the effect of retention interval on distractor intrusions in Experiment 4. The black horizontal bar covers the 95% highest-density interval (Kruschke, 2011)

Table 6: Bayes Factors for Linear Mixed Effects Models of Response Proportions in Experiment 4

Dependent Variable (Proportion of Responses)	Serial Position	Retention Interval	Serial Position x Retention Interval
Serial Position = Input Position			
Correct	$2.1 * 10^8$	0.21	0.03
Transposition	$4.8 * 10^{10}$	0.18	0.18
Distractor Intrusion	59	0.18	0.06
NPL	0.92	0.15	0.53
Serial Position = Output Position			
Correct	$4.2 * 10^8$	0.21	0.91
Transposition	0.17	0.17	0.26
Distractor Intrusion	483	0.18	0.05
NPL	534	0.15	0.05

The effects of output position are shown in Figure 12. As in Experiment 3, accuracy declined over output position. Whereas transposition errors were unaffected by output position, distractor intrusions (and NPL errors) increased, contrary to what would be expected from distractor decay. The BF for these effects can be found in the lower part of Table 6.

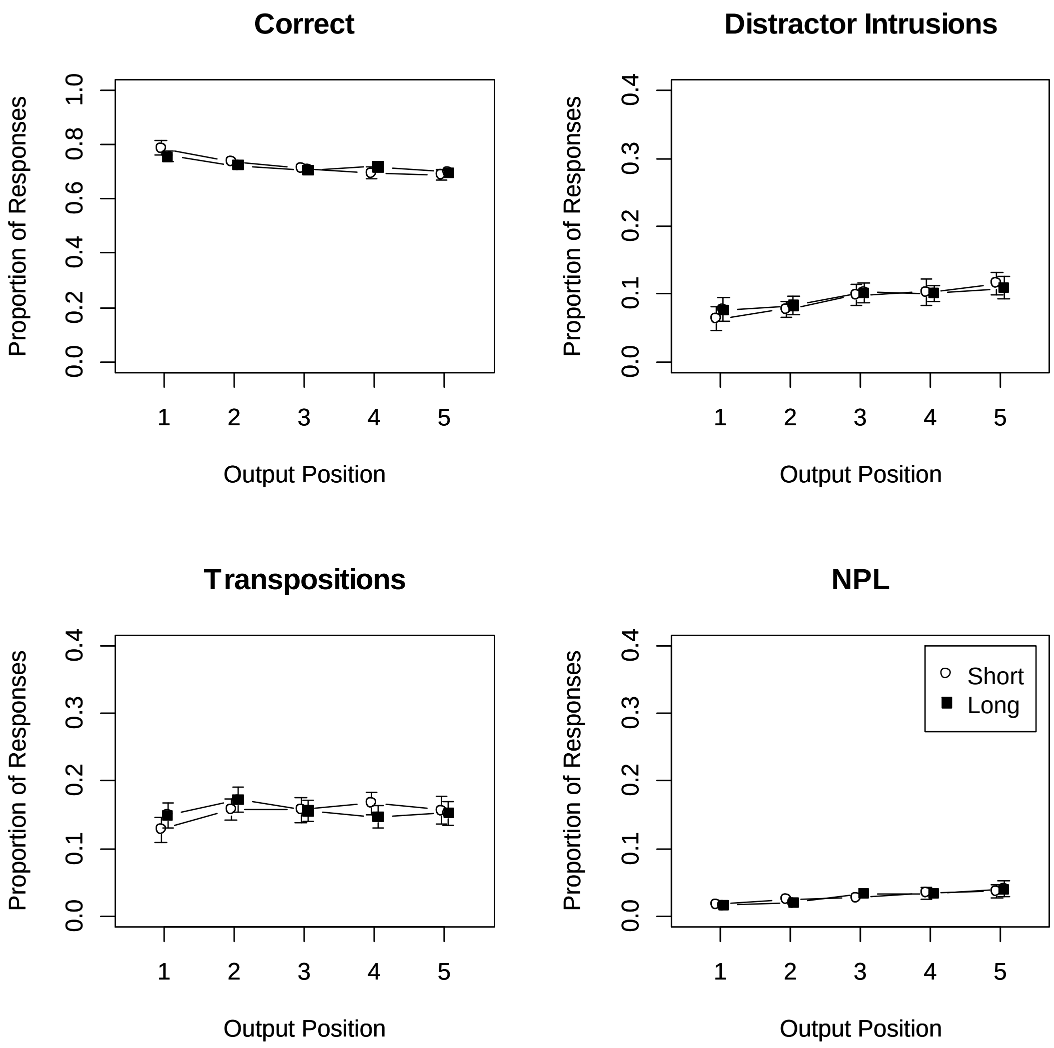


Figure 12: Proportion of response categories by output serial position and retention-interval condition, Experiment 4. Error bars represent 95% confidence interval for within-subjects comparisons (Bakeman & McArthur, 1996)

We again tested whether distractor intrusions declined with increasing time between their encoding and the test at which they intrude by regressing the proportion of distractor intrusions in the input-output matrix on Δt and on the retention-interval condition. Table 7 contains the distractor input-output matrices, and Figure 13 presents the results of the regression. As in Experiment 3, there was a tiny tendency for distractor intrusions to increase over longer time intervals, though the posterior 95% credible interval again included zero.

Confirming our initial analysis, there was no effect of the retention-interval condition on distractor intrusions. Equivalent results were obtained with a regression model predicting the proportion of distractor intrusions among all errors.

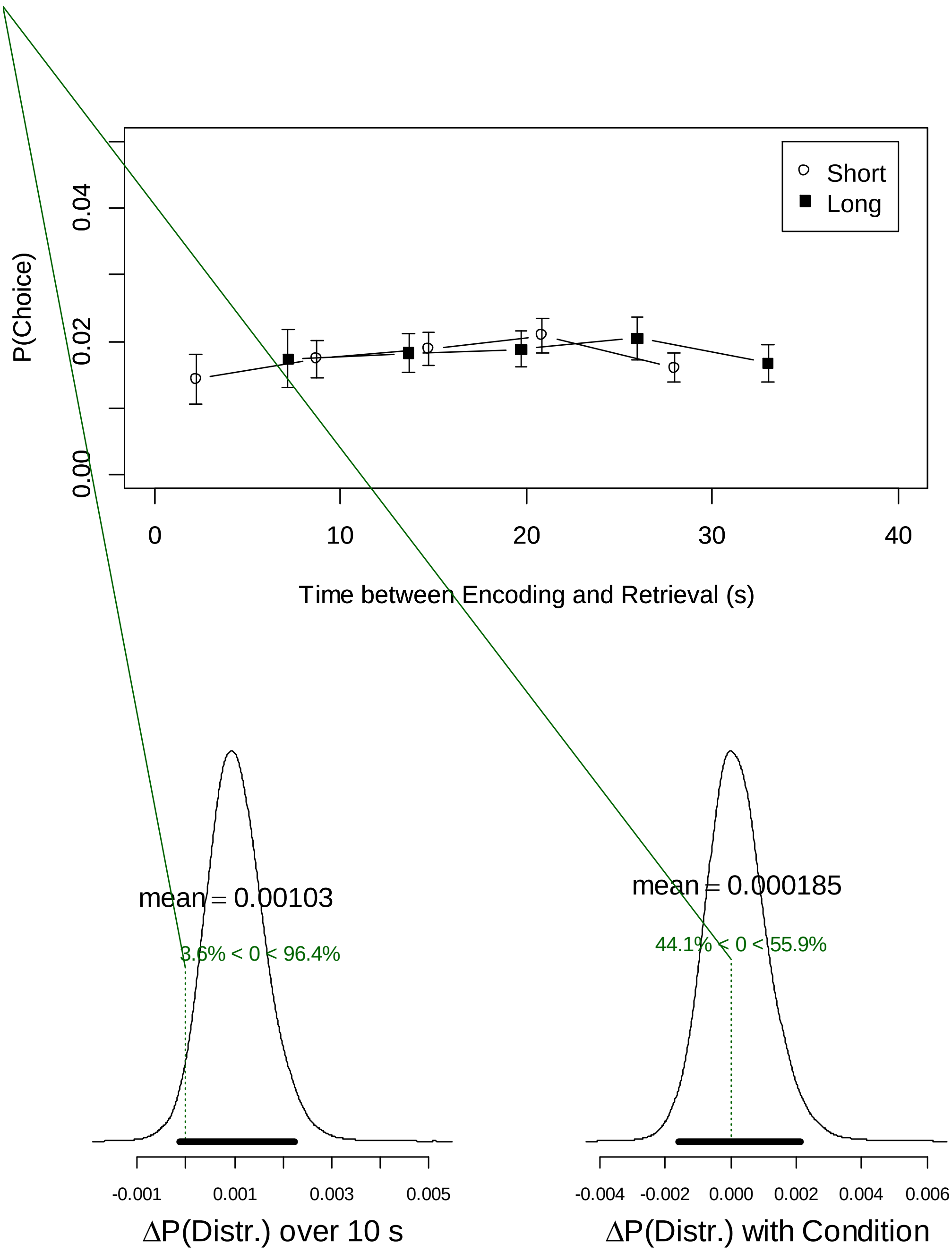


Figure 13: Top: Proportion of distractor intrusions as a function of the time between encoding of a distractor and the test at which it intrudes, Δt, in Experiment 4. Data were aggregated for plotting into five bins of Δt; error bars represent 95% confidence intervals for

within-subjects comparisons. Bottom: Posterior probability densities for changes in the probability of distractor intrusions as a function of Δt and of retention-interval condition as implied by the posterior densities of the regression parameters.

The final analysis again pertains to distractor intrusions as a function of their relative position in relation to the item they replace. Figure 14 shows an increased prevalence of distractor intrusions in relative position 0, further confirming that distractors tend to intrude by replacing the immediately preceding item. The BF for the effect of relative position was $1.8 * 10^7$.

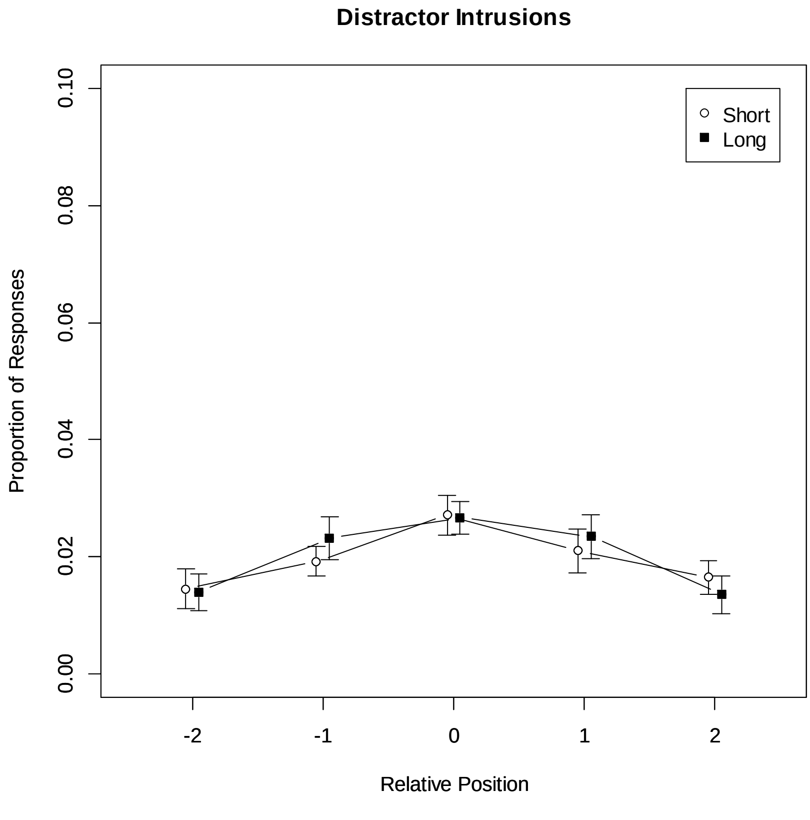


Figure 14: Distractor intrusions by relative position (proportion of total responses), Experiment 4. Error bars represent 95% confidence interval for within-subjects comparisons (Bakeman & McArthur, 1996).

Table 7. Distractor Input-Output Matrices and Corresponding Δt Values by Retention-Interval Condition, Averaged over Participants, Experiment 4

	P(Distractor Intrusions) Output Position					Δt (s) Output Position				
Input Position	1	2	3	4	5	1	2	3	4	5
Short Retention Interval										
1	.008	.015	.016	.019	.013	9.9	15.4	19.4	23.0	26.3
2	.011	.016	.019	.021	.019	7.4	12.9	16.9	20.6	23.9
3	.015	.014	.019	.019	.029	5.0	10.5	14.4	18.1	21.4
4	.023	.020	.026	.023	.028	2.5	8.0	12.0	15.6	18.9
5	.006	.013	.019	.020	.027	0	5.5	9.5	13.1	16.4
Long Retention Interval										
1	.012	.015	.019	.020	.017	14.9	20.4	24.3	27.8	31.1
2	.011	.011	.020	.013	.019	12.4	17.9	21.8	25.3	28.7
3	.019	.018	.021	.021	.020	10.0	15.4	19.3	22.9	26.2
4	.018	.024	.025	.025	.030	7.5	13.0	16.9	20.4	23.7
5	.017	.016	.016	.021	.024	5.0	10.5	14.4	17.9	21.2

Discussion

Experiment 4 replicated the effects of input position and output position on all four response categories that were observed in Experiment 3. In addition, Experiment 4 provided strong evidence against the assumption that distractor representations decay in working memory. Distractors were erroneously chosen for recall much more frequently than NPLs, demonstrating that distractors were encoded into working memory and remained there, to some extent, until test. People's inclination towards choosing distractors did not diminish over a five-second retention interval. In addition, as in Experiment 3 there was no hint of distractor intrusions declining over the range of Δt values across the entire input-output matrix.

Unless it is assumed that distractors are actively maintained in working memory through rehearsal or refreshing, this finding is incompatible with the assumption of distractor decay. As it is highly implausible that participants made an effort to maintain distractors in memory, Experiment 4 adds to the evidence against decay of information in working memory that is no longer relevant, such as distractors or memory items from previous trials (Berman, Jonides, & Lewis, 2009). This conclusion converges with the substantial body of evidence against decay of relevant representations in working memory, at least for verbal materials (Lewandowsky, Duncan, & Brown, 2004; Lewandowsky et al., 2010; Lewandowsky, Oberauer, & Brown, 2009; Oberauer & Lewandowsky, 2008, 2013, 2014).

General Discussion

We set out to test two key assumptions of the SOB-CS model of working memory: First, processing of distractors impairs maintenance of other contents of working memory because representations involved in distractor processing are inadvertently encoded into working memory, where they interfere with the memoranda. Second, free time following distractor processing is used for unbinding the last-used distractor representation from its context, thereby effectively removing it from working memory. The four experiments presented in this article support both assumptions. This support rests on the conjunction of three findings: (1) Memory is improved, and distractor intrusions are reduced, with longer free time; (2) this happens also when free time cannot be used for rehearsing the memoranda; and (3) distractor intrusions do not decline as a function of the total retention interval, ruling out distractor decay.

Distractor Encoding

All four experiments showed that distractors are chosen much more frequently than non-presented lures at recall, providing unambiguous evidence that the distractors have been encoded into memory, and compete with the memory items at recall. This competition directly reflects one form of interference postulated in SOB-CS, interference by confusion. A previous series of experiments has already provided evidence for the second form of interference in the model, interference by superposition (Oberauer, Farrell, et al., 2012). Jointly, these two sets of experiments make a strong case for the mechanisms of interference between distractors and memoranda as incorporated in SOB-CS.

Our experiments also add to the evidence for the more specific assumption in SOB-CS that distractors are bound to the positions of the immediately preceding distractor: In Experiments 3 and 4, distractor intrusions most often replaced the list item in the same input position (i.e., relative position 0), and distractor intrusions fell off gradually with increasing positional distance to the immediately preceding item. These findings confirm the locality constraint for distractor intrusions first documented by (Oberauer, Farrell, et al., 2012). In Experiment 1, distractors more often replaced the immediately following item rather than the immediately preceding one. This result is to some extent also noticeable in the SOB-CS simulations (see Figure A2), but the model still produced a peak at relative position 0, which was not found in the experimental data. This discrepancy hints at the possibility that, under some circumstances, distractor representations are bound to the position of the next item rather than of the preceding item. Future research might investigate systematically under which conditions which variant of the locality constraint holds for distractor intrusions.

Distractor Removal

The second assumption in SOB-CS, removal of distractors during free time, entails the prediction that distractor intrusions decline with longer free time following each distractor. This prediction was confirmed by the model simulations (Figures A1, A3, and A4) and empirically supported across Experiments 1 to 3. This observation on its own is not diagnostic, however, because it is open to two alternative explanations. First, it could reflect selective rehearsal or refreshing of memoranda during free time, boosting memory strength for the memoranda. This would result in fewer errors overall, including fewer distractor intrusions. Second, the decline of distractor intrusions could reflect decay of distractor representations during the free time, while memoranda are maintained through rehearsal or refreshing.

Experiment 2 ruled out the first alternative explanation: We observed a reduction of distractor intrusions, and an improvement of memory, with longer free time following distractors that preceded the entire memory list. During these free-time intervals no rehearsal or refreshing was possible because the memoranda have not yet been presented. It follows that the decline of distractor intrusions with increased free time cannot reflect greater competition from strengthened memoranda.

Experiments 3 and 4 jointly rule out the second alternative explanation: The notion that distractors decay implies that the proportion of distractor intrusions must decline over time. In both experiments we varied the time between encoding a distractor and the test at which it could intrude over a range of more than 30 s, and found that the proportion of distractor intrusions was unaffected by that variation in time. In addition, Experiment 4 refuted a prediction following directly from the assumption of distractor decay: The prevalence of distractor intrusions should decline over an unfilled retention interval. There was no hint of such a decline in the data. The use of Bayesian statistics enabled us to measure the strength of evidence against the predicted effect, and it turned out to be strong: The data of Experiment 4 were 12 times more likely under the assumption that distractors do *not* decay than under the assumption that they do.

After having ruled out the two alternative explanations for the decline of distractor intrusions over free time, we argue by exclusion that this effect reflects the removal of distractors, as assumed in SOB-CS. This conclusion converges with evidence from experiments on the updating of working memory, which also show that updating involves the removal of outdated information (Ecker, Lewandowsky, & Oberauer, 2014; Ecker, Oberauer, & Lewandowsky, 2014). Removal of representations that are no longer needed appears to be among the basic operations of the working memory system.

Upon reflection, this is not surprising: To serve its function of holding available relevant information for ongoing cognitive activities, the working memory system needs to keep pace with the train of thought and with changes in the environment. Doing so requires updating working-memory contents several times per second. This means that outdated information must be cleared out at the same rate. Time-based decay cannot serve this function, for two reasons. First, there is strong evidence that at least *verbal* contents of working memory do not decay (Lewandowsky et al., 2009; Oberauer & Lewandowsky, 2013, 2014). Second, findings that are often cited in support of decay for non-verbal materials – a modest decline of accuracy over several seconds – imply a decay rate much too slow for clearing out working memory at the pace at which our stream of consciousness progresses (McKeown & Mercer, 2012; Mercer & Duffy, 2015; Mercer & McKeown, 2014; Ricker &

Cowan, 2010; Ricker, Spiegel, & Cowan, 2014; Zhang & Luck, 2009). Working memory could not function as well as it does without removing outdated information, and the present experiments confirm a role for removal of distractors in keeping working memory working.

Alternative Theories of Complex Span

In addition to supporting SOB-CS, our findings challenge other theories of working memory, in particular alternative explanations for the detrimental effect of distractor processing on memory performance. One alternative explanation is that distractor processing prevents rehearsal or refreshing of the memoranda, leaving them to decay (Barrouillet et al., 2007; Towse et al., 2000). This approach has difficulties explaining two aspects of our findings. First, it cannot explain the proactive interference of distractor processing on memory observed in Experiment 2. Second, it is called into question by the evidence against distractor decay in Experiments 3 and 4: Decay theories would have to be embellished by a mechanism that enables distractors to escape decay: They need to be maintained at a constant level of strength exceeding that of NPLs. One possibility, building on the suggestion of Ricker and Cowan (2014) that short-term consolidation reduces the decay rate, is to assume that the present experiments allowed sufficient time for memory items and distractors to be consolidated to a degree that decay becomes negligible. As the timing of our experiments is typical for experiments on verbal and spatial WM, this assumption would render decay irrelevant for most experiments in that field. Below we discuss an alternative account through which the decay assumption could be salvaged.

Another alternative view is that distractors displace memoranda from a limited-capacity store (Unsworth & Engle, 2007), or take away attentional capacity from the memoranda (Chen & Cowan, 2009). These accounts are challenged by our data in two ways. First, neither alternative can explain the proactive interference of distractor processing observed in Experiment 2: Processing cannot displace representations from primary memory before they enter primary memory, and processing cannot take away attentional resources from memory representations that have not yet received any such resources. Second, it is not clear how these accounts can explain the beneficial effect of free time. Once a representation is displaced from primary memory, or depleted of attentional resources, it is difficult to see how subsequent free time can be used to undo the damage. Assuming that somehow it is possible to restore displaced representations to primary memory, or give back resources to them during free time, it remains mysterious why an extended retention interval cannot be used for the same purpose.

A third alternative could be formulated on the basis of unitary theories of memory that reject the distinction between working memory and episodic long-term memory, such as the SIMPLE model of memory (Brown et al., 2007) or the temporal-context model (Howard & Kahana, 2002; Sederberg, Gershman, Polyn, & Norman, 2011). These models share with SOB-CS the assumption that representations of events are associated to a context evolving over time. Applied to complex span, these models would assume that memoranda and distractors are associated to overlapping contexts, so that distractors interfere with recall of the memoranda. Proactive distractor interference, as observed in Experiment 2, arises from contextual overlap between the distractor series and the subsequent memory list. This kind of explanation could also be formulated within dual-store models together with the assumption that secondary or long-term memory contributes substantially to behavior in complex span tasks (Davelaar, Goshen-Gottstein, Ashkenazi, Haarmann, & Usher, 2005; Unsworth & Engle, 2007).

What is unclear is how these models could account for the beneficial effect of free time. One possibility is that free time increases the temporal distinctiveness between distractors and memoranda, that is, it reduces their contextual overlap. This explanation would work well for Experiment 2, but not so well for the remaining experiments in which memory items and distractors alternate. In Experiments 1 and 3 longer free time increases the temporal distance between each distractor and the next item, but at the same time increases the temporal distance of list items to the time of recall. Temporal-distinctiveness models assume that, everything else being equal, distinctiveness decreases as events recede into the past (Brown et al., 2007). Longer free times therefore reduce the distinctiveness of memory items, in particular those early in the list, from temporally proximal other list items and distractors. A simulation with SIMPLE (see Appendix B) shows that at early list positions this loss of temporal distinctiveness outweighs the benefit of a larger temporal separation of memoranda and distractors, leading to slightly more distractor intrusions in the longer free-time condition. We conclude that temporal distinctiveness offers at best an incomplete explanation of the beneficial effect of free time.

A complete account of the present data could be construed by combining assumptions from several existing theories. Consider a dual-store model with a primary memory that is subject to decay, and a secondary memory with a continuously evolving temporal context. Memory items and distractors are encoded into secondary memory by associating them to their temporal contexts. Only memory items are maintained in primary memory through refreshing. At test, information from both primary and secondary memory is retrieved and integrated to select a recall candidate. In this way, distractors retrieved from secondary memory are selected more often than NPLs. When distractors are processed in between encoding of memory items (Experiments 1 and 3), free time is beneficial because it is used to refresh the memory items, while any representation of distractors in primary memory fades away through decay. When distractors precede presentation of the memory list (Experiment 2), free time following them is beneficial because it increases their temporal separation from the memoranda, reducing the chance that they are confused with a memory item during retrieval from secondary memory. Alternatively, the beneficial effect of free time in Experiment 2 could be explained by drawing on the assumption of Ricker et al. (2014) that free time can be used to actively change the context between a previous episode (in our case: processing of the six distractors) and the currently to-be-remembered episode (in our case: the memory list). The finding that an extended retention interval did not reduce distractor intrusions (Experiment 4) could be explained by assuming that distractors have already completely decayed from primary memory once recall commences regardless of the retention interval, so that distractor intrusions come only from secondary memory. This account could explain all our findings, albeit somewhat less parsimoniously than SOB-CS because it requires two different explanations for the free-time benefit, one for when distractors precede the memory list and another for when they alternate with the memory items. We also note that this account is post hoc, though arguably plausible because it draws on assumptions that already exist in the literature.

A final alternative explanation deserves consideration: Rather than removing distractor representations from working memory, an associative memory such as SOB-CS could also bind distractors to associate each stimulus to a context reflecting its role in the task. Memory items could be bound to a "memory" context, and distractors to a "distractor" context. Free time following a distractor could be used to create and gradually strengthen these bindings. At test, the role context can be used to filter out distractors, thereby reducing distractor intrusions and improve recall of the memory items. In this way, distractors are not removed from memory but effectively removed from recall. We have not implemented this alternative mechanism in SOB-CS yet, but we see no principled reason why it should not work.

Conclusions

The present experiments provide further support for the SOB-CS model of complex span, and at the same time challenge several alternative theories. Looking beyond the present experiments, SOB-CS accounts for a broad range of findings from working-memory span paradigms: It explains the serial-position curves and the error patterns of simple and complex span tasks (Oberauer, Lewandowsky, et al., 2012). It explains the detrimental effect of distractor processing, and why that effect is mitigated by free time following distractors (Oberauer, Lewandowsky, et al., 2012; and the present experiments). It correctly predicts that increasing the number of distractor operations to be carried out in complex span has no effect on memory, unless the distractors differ substantially from each other (Lewandowsky et al., 2010; Lewandowsky, Geiger, & Oberauer, 2008; Oberauer & Lewandowsky, 2014). SOB-CS correctly predicts the conditions under which similarity between memory items and distractors is helpful (Oberauer, Farrell, et al., 2012). It also predicts the locality constraint for distractor intrusions (Oberauer, Farrell, et al., 2012; and the present experiments), and the related finding that distractor processing impairs memory locally in adjacent list positions, not globally throughout the list (Farrell et al., 2016). Moreover, the model explains why distractors from different content domains impair memory less than distractors from the same content domain (Oberauer, Lewandowsky, et al., 2012). Finally, SOB-CS was also used to reproduce the pattern of correlations between simple and complex span (Oberauer, Lewandowsky, et al., 2012) and the pattern of articulatory rehearsal in immediate serial recall of word lists (Lewandowsky & Oberauer, 2015). No other theory or model of working memory accounts for a comparably large number of phenomena from working-memory span tasks.

Although many details in SOB-CS certainly leave room for improvement, the weight of the evidence lends credibility to the model's core assumptions: Information that people attend to is encoded into working memory, including memory items and distractors. Information is encoded into working memory by bindings to a context, such as a temporal or spatial position. Working memory capacity is limited by two kinds of interference between representations, interference by confusion and interference by superposition. Finally, representations in working memory do not fade away over time; rather they have to be unbound from their context when they are no longer needed.

Appendix A: Simulations with SOB-CS

Here we present simulations of Experiments 1 to 3 with SOB-CS to confirm that the predictions we test actually follow from the model. For the retention-interval manipulation in Experiment 4 SOB-CS predicts no effect because the model does not do anything in an unfilled retention interval. A simulation would be identical for both conditions, so running it is unnecessary. A detailed description of SOB-CS can be found in (Oberauer, Lewandowsky, et al., 2012); here we only note additions and changes to the original model that were necessary for applying it to the present experiments.

Experiment 2, in which a series of distractors preceded presentation of the entire memory list, is a new paradigm to which SOB-CS has never been applied. Applying the model to this paradigm requires new assumptions about the context to which the distractors and the memory items are bound. From the model of (Farrell, 2012), a close relative of SOB-CS, we borrow the notion of hierarchically embedded contexts that reflect the embeddedness of events (see also Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999). Specifically, we assume that each trial is represented as an episode that is integrated by a common trial context, and within it individual events – distractors and memory items – are distinguished by position markers. The representations of each event are therefore bound to a context representation consisting of two components, the trial component, which remains constant within a trial, and the position component, which changes with each event.

To construct these contexts we first created two sets of six position markers – one for the distractors and one for the memory items – exactly as in previous applications of SOB-CS and its predecessors (Farrell, 2006; Oberauer, Lewandowsky, et al., 2012): Each position markers was a vector of 16 units with values between -1 and 1, and the similarity (vector cosine) between successive positions was controlled by a model parameter, s_p. For the position markers of memory items we set $s_p = 0.5$, its standard value. For the position markers of distractors we set $s_p = 0.8$. The high similarity between positions of subsequent distractors is motivated by the assumption in SOB-CS that changes in context occur only to the extent that distinguishing subsequent events is task relevant. For the same reason, the position markers in a complex span task are assumed to change only upon encoding a new item, but not with each new distractor (Oberauer, Lewandowsky, et al., 2012). Each position marker was concatenated with a 5-element vector for the trial context, which was generated at random and remained constant throughout the trial.

In all other regards, the simulations were based on SOB-CS as described in (Oberauer, Lewandowsky, et al., 2012). We used the standard parameter values from that publication, with the following exceptions: First, because the addition of an episode context resulted in longer context vectors, the average energy calculated as an indicator of novelty of each stimulus was higher, and therefore we needed to adjust the parameters of the equation translating energy into encoding strength (Equation 4 in Oberauer et al., 2012). We set the energy threshold $e = -2500$ and the gain g to .002. Second, we found that we had to increase the output interference parameter N_o to 4.5 to reproduce the decline of accuracy over output positions in Experiment 3.

Figures A1 to A6 present predictions of SOB-CS for Experiments 1 to 3 in the same layout as the data figures in the main body of the text.

Figure A1

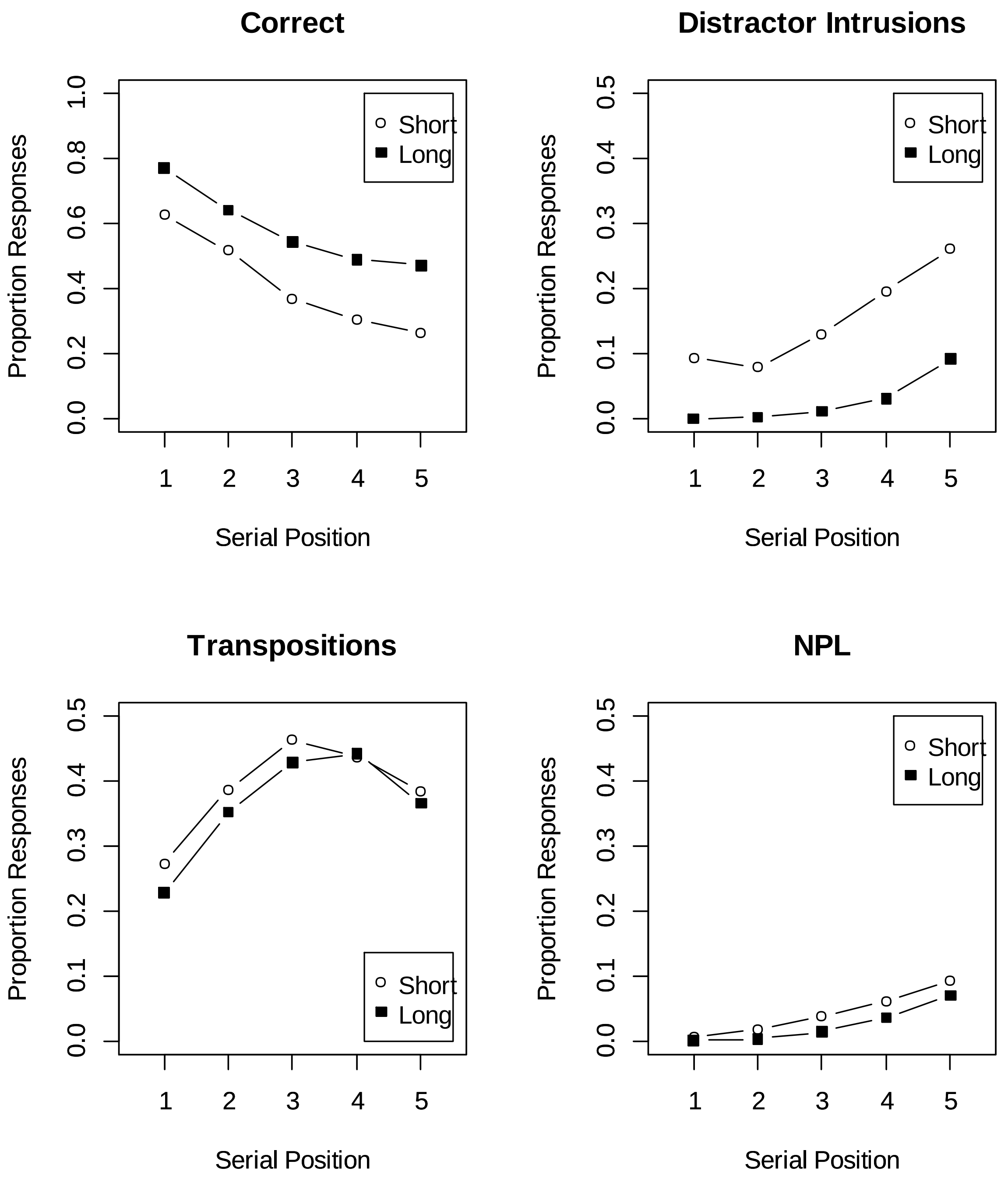


Figure A1: SOB-CS simulation results for proportion of response categories by serial position and free-time condition, Experiment 1. This figure presents the model predictions for Figure 3.

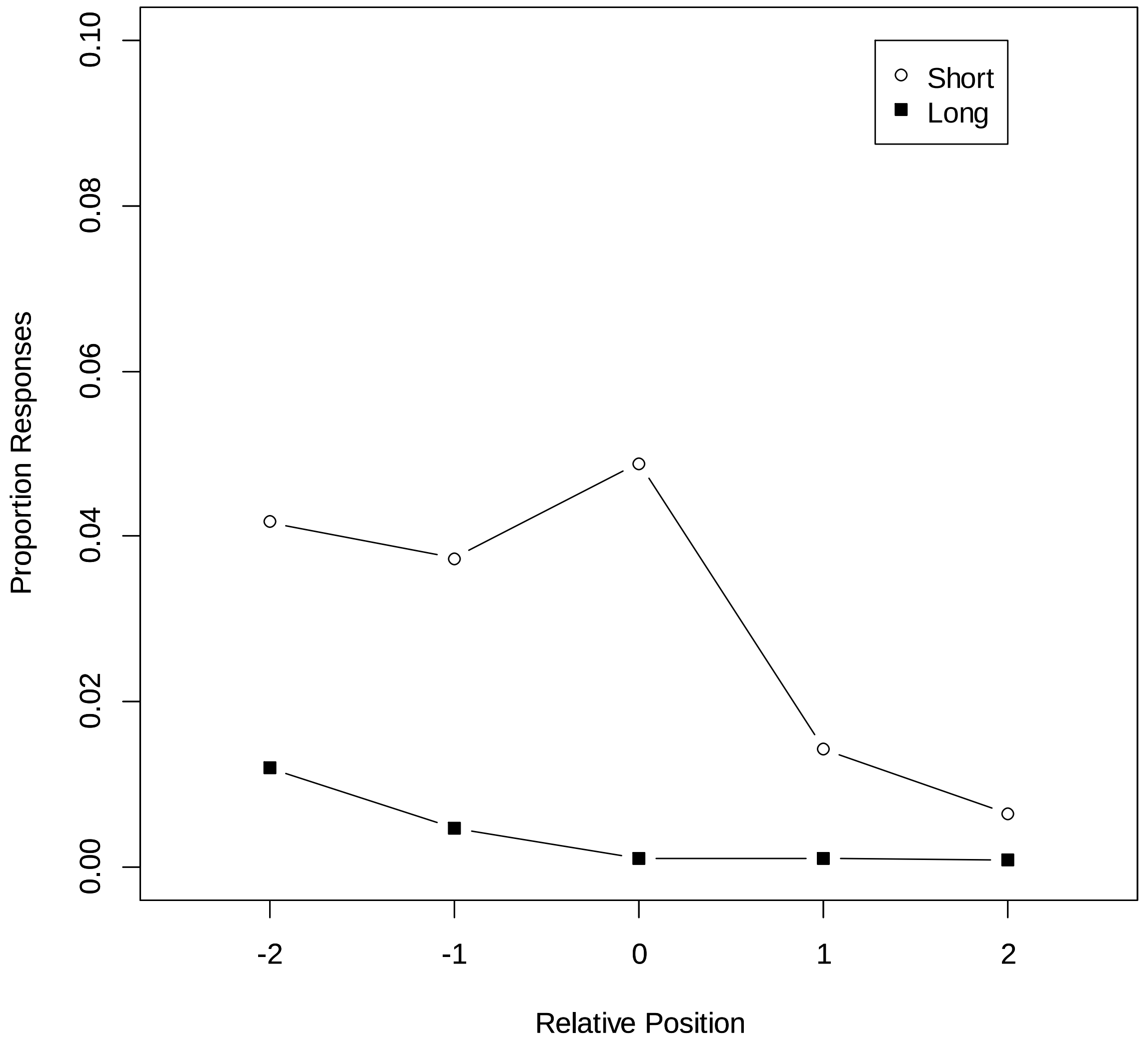


Figure A2: SOB-CS simulation results for distractor intrusions by relative position, Experiment 1. This figure presents the model predictions for Figure 4.

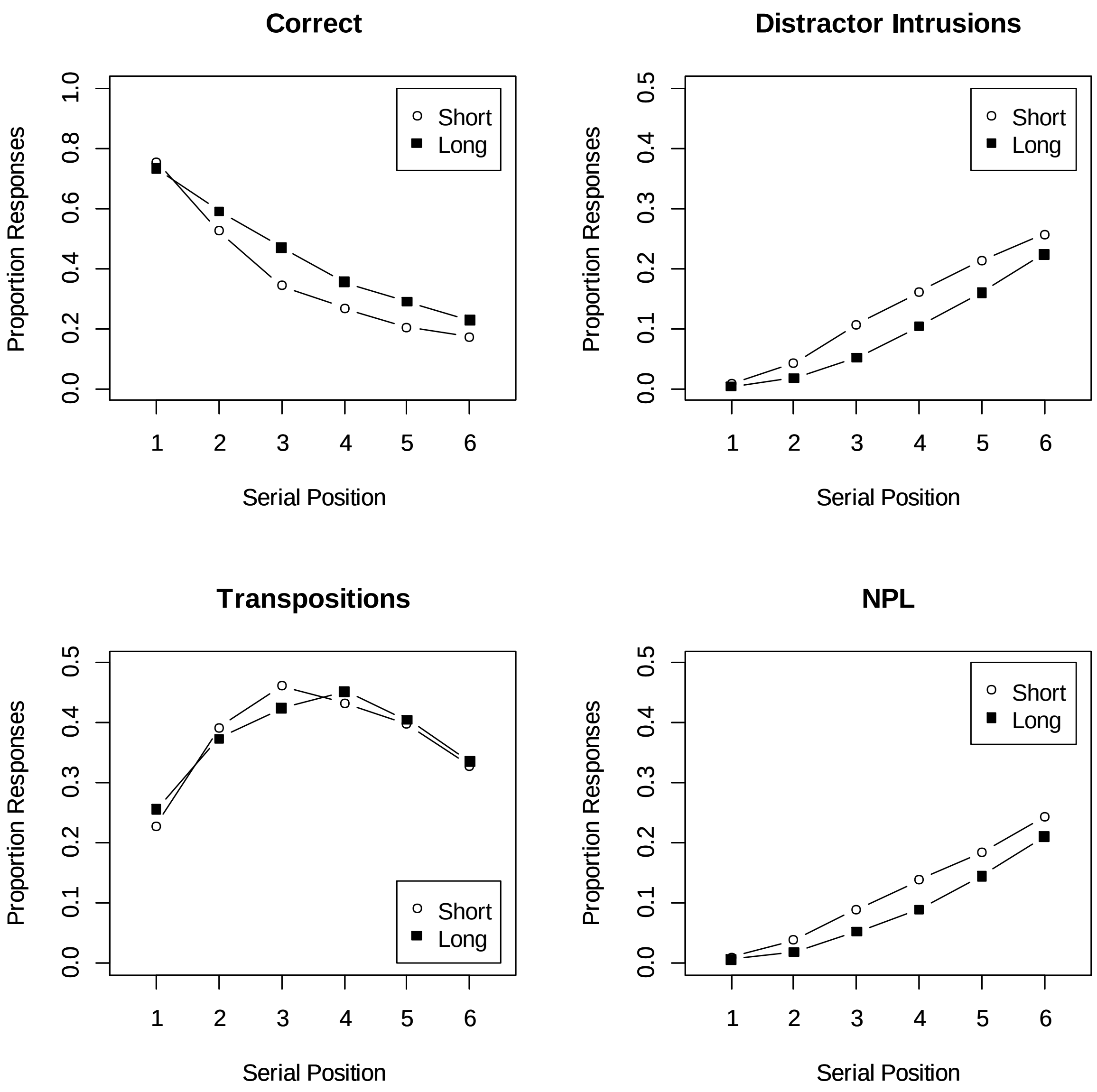


Figure A3: SOB-CS simulation results for proportion of response categories by serial position and free-time condition, Experiment 2. The filled-long-time condition was not simulated because its deviation from the two free-time conditions depends only on the assumption made about interruption of removal by concurrent processing, which has to be added to the model. This figure presents the model predictions for Figure 5.

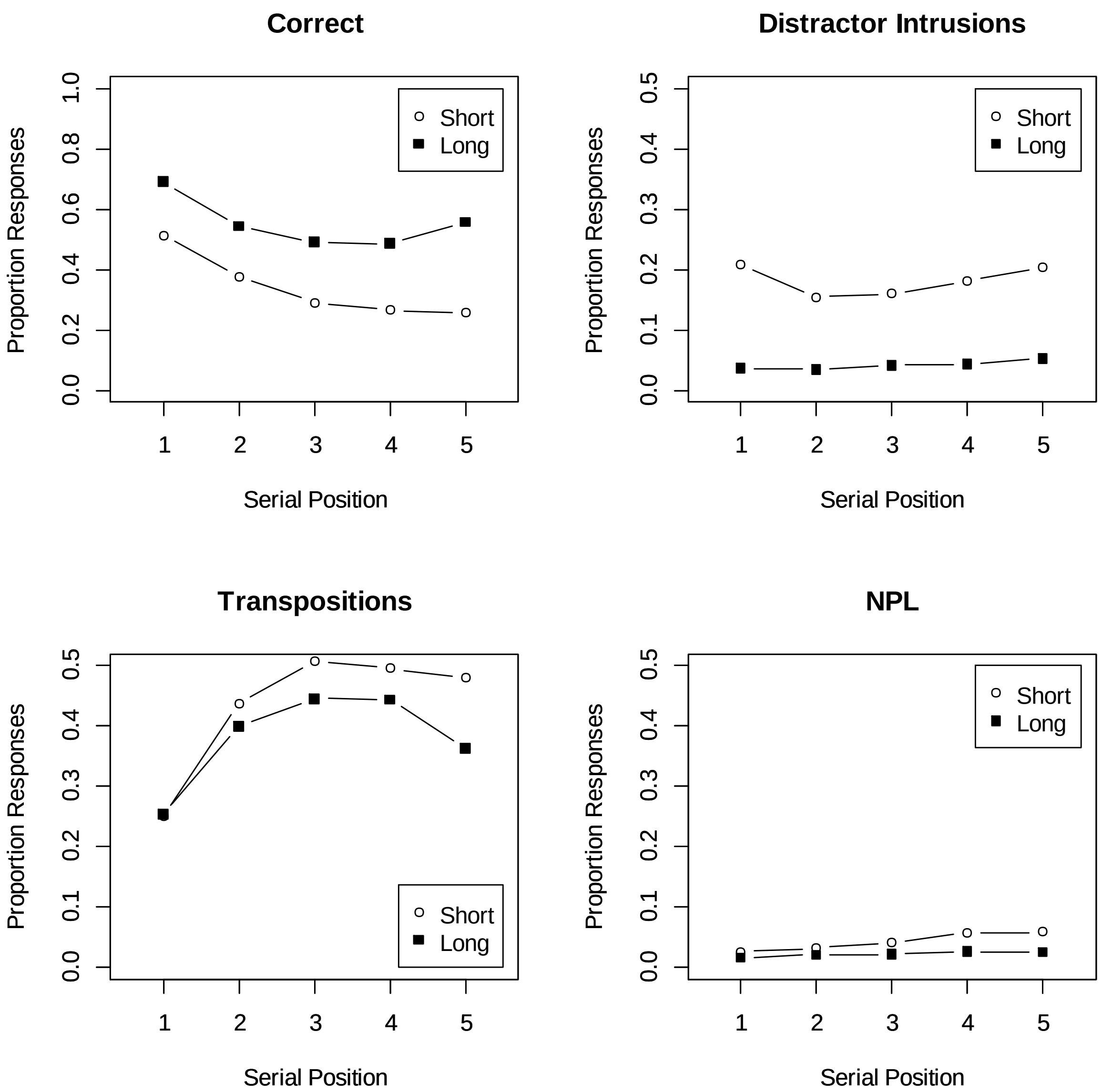


Figure A4. *SOB-CS simulation results for response categories by input serial position of the tested item, Experiment 3. This figure presents the model predictions for Figure 6.*

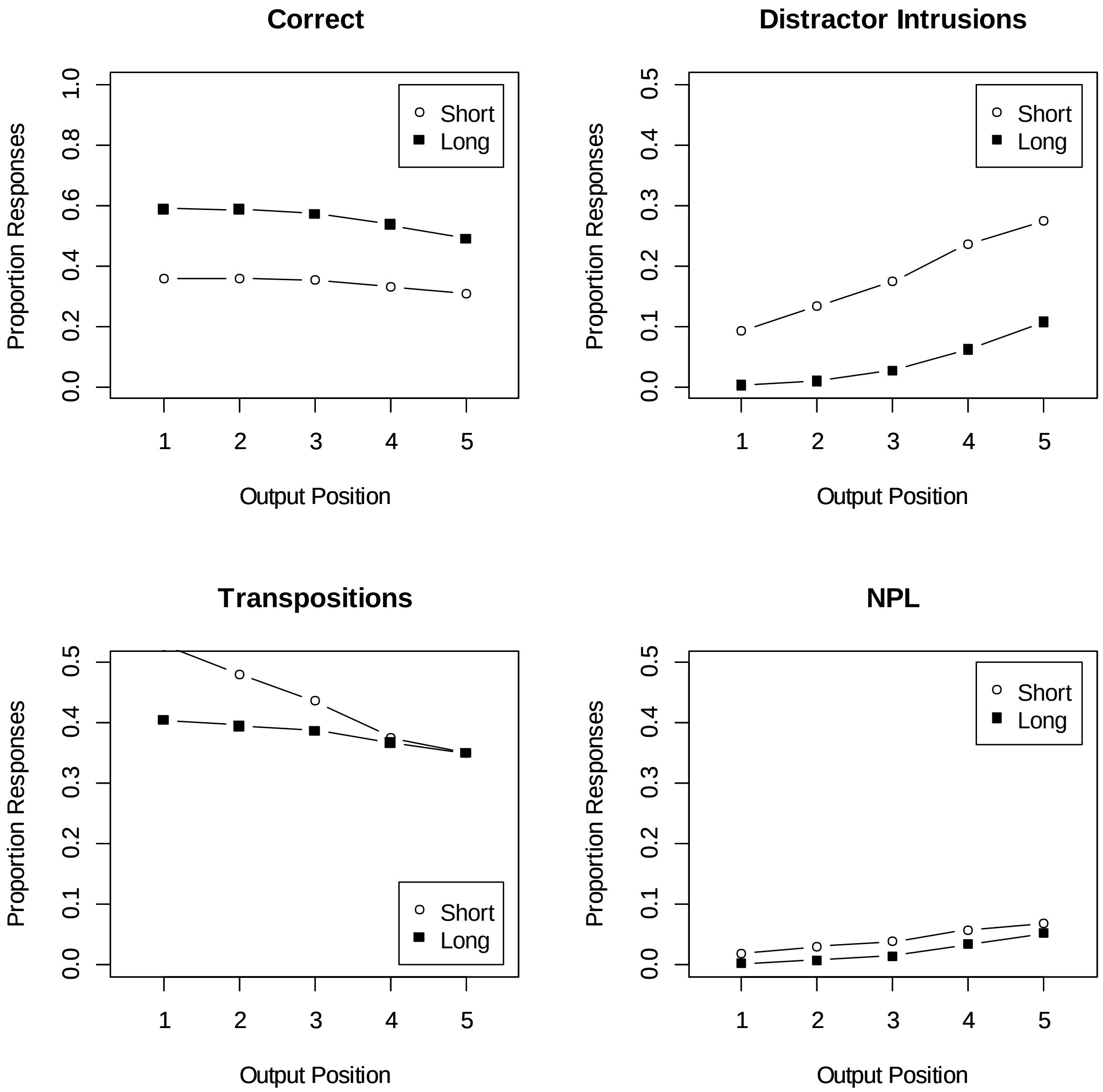


Figure A5. *SOB-CS simulation results for response categories by output position, Experiment 3. This figure presents the model predictions for Figure 7.*

Figure A6 :

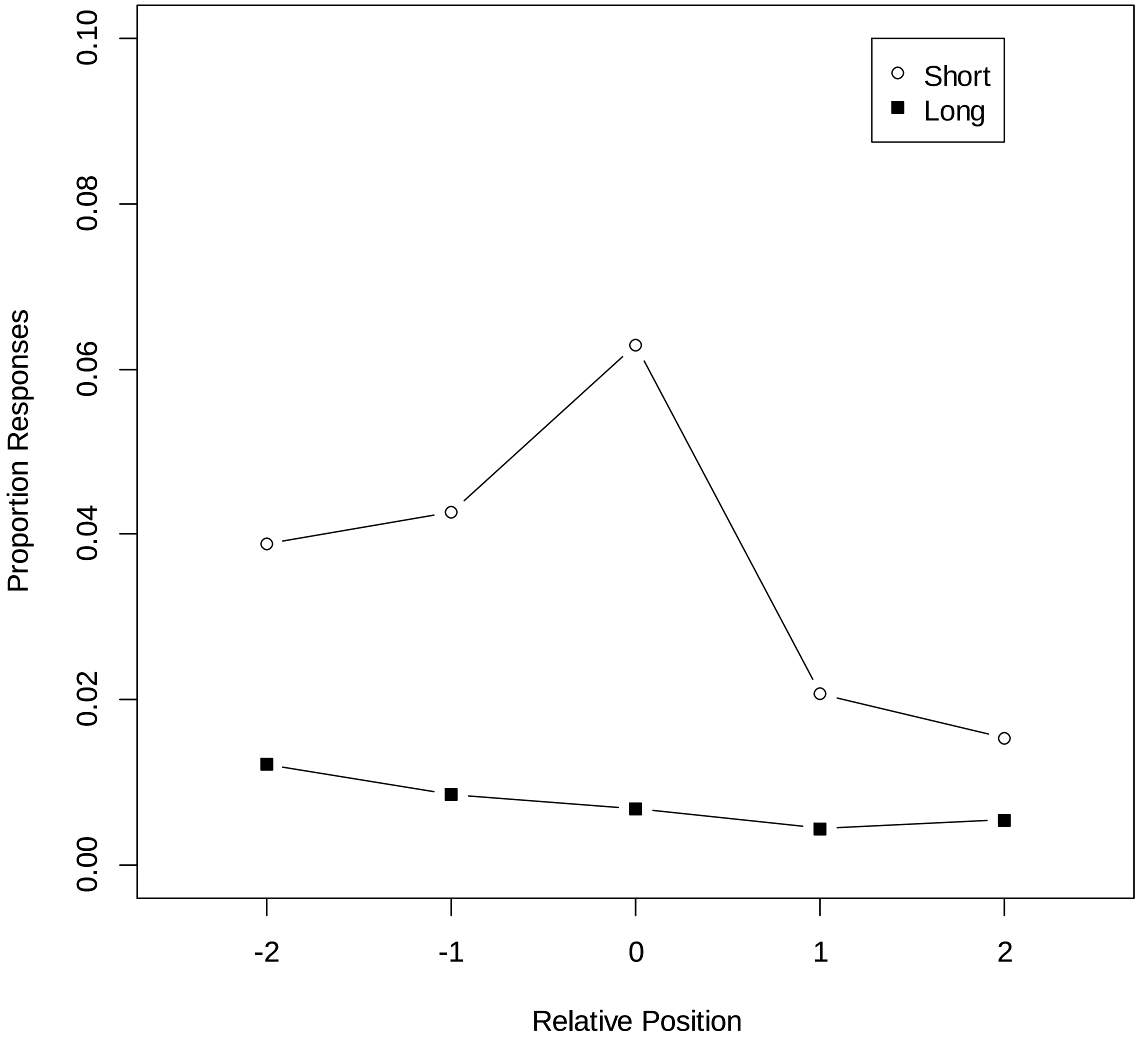


Figure A6: SOB-CS simulation results for distractor intrusions by relative position, Experiment 3. This figure presents the model predictions for Figure 9.

Appendix B: Simulation of Experiment 1 with SIMPLE

We explored whether SIMPLE (Brown et al., 2007), a formal temporal-distinctiveness model of memory, can explain the free-time effects in complex span. To accommodate the complex-span paradigm we implemented a two-dimensional version of SIMPLE (Lewandowsky et al., 2004) in which events – memory items and distractors – are represented as points in a two-dimensional mental space with a temporal dimension and a binary category dimension that separates items from distractors. At test, the location of the searched-for event in mental space is reinstated as a retrieval cue, and the probability of retrieval for each representation anywhere in mental space is a decreasing function of its distance to that retrieval cue. In our application of SIMPLE to complex span, all memory items have distance 0 on the category dimension and all distractors have distance 1. Thereby, the category dimension ensures that at equal temporal distance items are more likely to be recalled than distractors. The distance of all items and distractors to the retrieval cue on the temporal dimension is given by their distance on a log-transformed time axis that recedes into the past from the time of test, which we updated for each output position by adding 4 s per recalled item, in line with observed average recall times. Distances on the two dimensions are combined as weighted sums. The model had two free parameters, the distinctiveness parameter, c, and the weight for the temporal dimension, w (the weight for the category dimension equals $1-w$). Parameter c controls how steeply the confusability of representations falls off with increasing distance (see Brown et al., 2007); w controls the relative importance of time and category in determining distance (see Lewandowsky et al., 2004). We obtained a reasonably good approximation to the empirical serial-position curves and error proportions with $c = 8$ and $w = 0.85$. The results are shown in Figure B1. The model predicts better recall for long free times, in particular in later list positions, and this effect is due to a reduction of transposition errors: Longer free time increases the temporal separation between list items, making them less confusable. Longer free time also slightly reduced distractor intrusions at the end of the list, but increased them at the beginning. This reflects the trade-off between two effects of free time: On the one hand it increases distinctiveness by separating events on the time dimension; on the other hand, it reduces temporal distinctiveness by increasing the time between encoding and test, because the time dimension is logarithmically compressed as it recedes into the past. The latter effect accumulates at earlier list positions, which therefore benefit the least from longer free times.

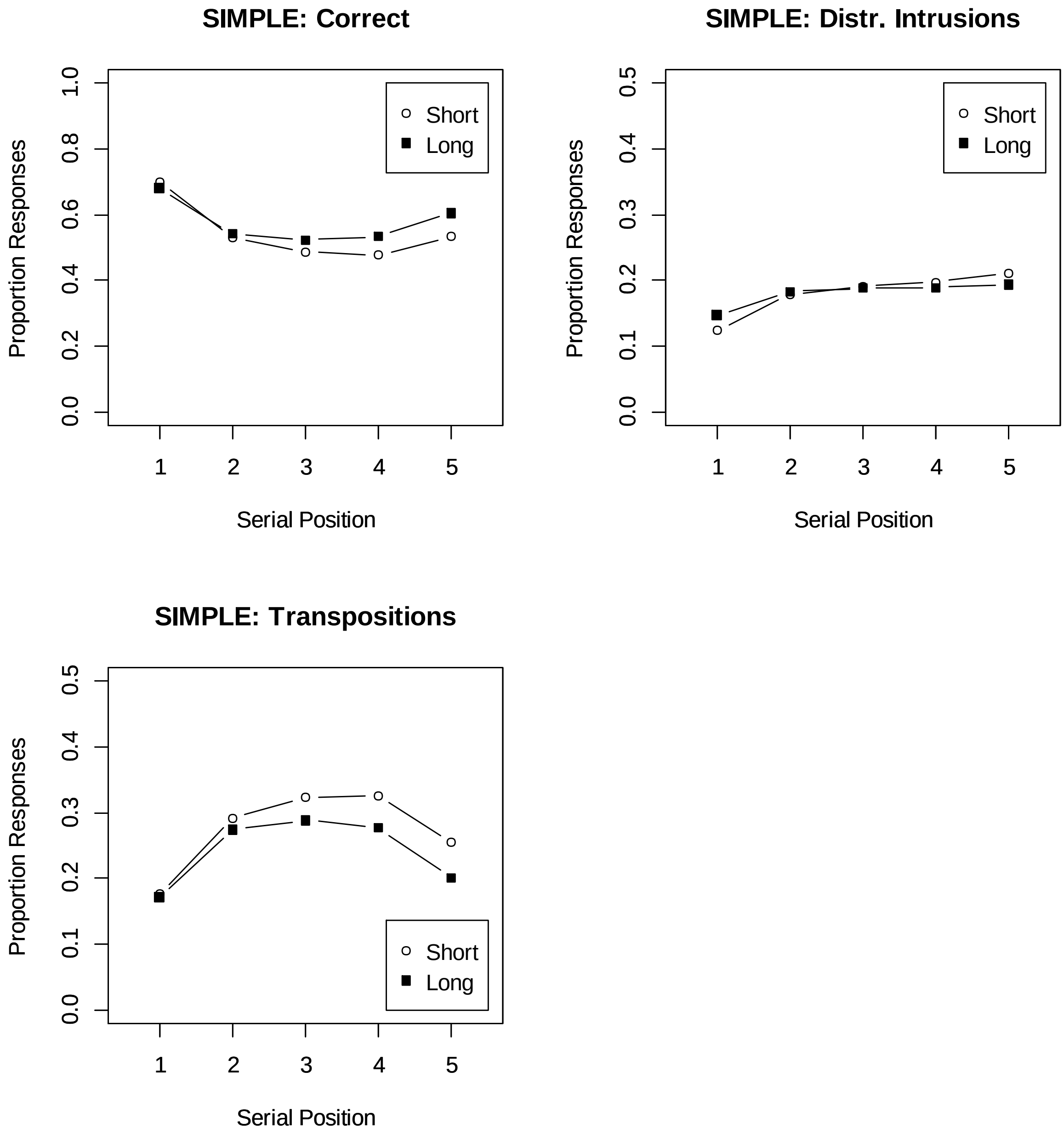


Figure B1: SIMPLE simulation results for response categories by serial position, Experiment 1.

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